The Second Stone Age:

Sustainability, Cement Transitions and

Making the Concrete Cornucopia, 1750-1850

by

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ABSTRACT

Humankind has entered another lithic epoch. Concrete is the modern stone. Since taking its contemporary form nearly two centuries ago, over five hundred billion tons of the gray matter have been deposited on the earth's crust. If this amount of concrete was used to build a sidewalk that was six feet wide and three inches thick, it could wrap around the equator over thirty-eight thousand times. The scale of production is tremendous, but only part of the story. Due to being fire-resistant, waterproof, plentiful, durable, malleable and relatively cheap, concrete has become the primary material used to transform the possibilities of human geography. Such megalithic environmental manipulations would be impossible without the sustained mass production of cement, concrete's essential ingredient. This dissertation explores the origins of the contemporary concrete cornucopia through an environmental history of the cement transitions that manifested it. Abundant fuel and raw materials as well as robust building regimes and demand for large-scale building on land and under water are necessary conditions for such cement transitions—defined as occurring whenever the production process and properties of cement are altered in a way that significantly changes construction possibilities. A central claim of this dissertation is that these requirements were met in southeastern Great Britain at the turn of the nineteenth century with the discovery of the cementitious properties of the natural cement stones in the London Clay at the moment of British imperial consolidation and industrial take-off. Ironically named "Roman cement," this natural cement substitute differed from its ancient namesake that had determined the building possibilities of western Europe for roughly two millennia. The British cement production system soon spread to other industrial regions with similar raw material

deposits, notably the northern United States, in a process of technology transfer that has since transformed the world. It is argued that this method of mass producing durable, quick-setting and waterproof cement with fossil fuels and its worldwide diffusion was foundational to the built environment's divergence from the organic economy. Thus began the Second Stone Age.

DEDICATION

In memory of David Graeber,
Batsh*t construction indeed.

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This dissertation has been under construction for many years. It has taken me from the trenches to the archives. As part of one of the least represented demographics in higher education, challenges have manifested in the form of material shortages, work interruptions and changing blueprints. Statistically speaking, you should not be reading this. The fact that you are is due largely to those who went above and beyond to help place the keystone in the long arch of my education and career.

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To the immovable, incorruptible and unstoppable elephant, who always moves forward; who never forgets to play; who finds watering holes in the driest of seasons; and who knows of pigs, coyotes and all other types of wildlife. How many crops have you ruined? You refused to listen when I had wanted to stop and showed me so many more frontiers. We have watched many sunsets and I am excited for those to come. I am most grateful for your companionship.

TABLE OF CONTENTS

CHAPTER ONE

INTRODUCTION

The Second Stone Age

As an aggregate of sand, gravel and portland cement—made with fossil fuels and calcium carbonate—concrete is a material free from the organic economy. This has enabled the mass production of over 500 billion tons of the anthropogenic stone since its invention nearly two centuries ago.[1] The scale of production is tremendous, but only part of the story. Modern concrete is significant for where and to what end it is used. All human societies exist within environmental bounds. As a fire-resistant and waterproof material that is abundant, durable, malleable and relatively cheap, concrete has become the primary substance used to manipulate those parameters. It holds back the seas with seawalls and piers. It harnesses rivers with hydroelectric dams, levees and dikes. It extends rails and roads over rivers and ravines. It facilitates dense urban settlement with foundations, sanitation systems and energy infrastructure. It has many other applications that determine the possibilities of modern human geography.[2] This dissertation explores the origins of the contemporary concrete cornucopia through an environmental history of the cement transitions that manifested it.

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1 Today, if one divides the amount of concrete produced annually by the global population, each person, on average, consumes nearly one ton of concrete per year. The distributional breakdown, although not related to impact, includes "about 37% of the mass present in urban areas, 21% associated with rural housing, 1.3% with rural roads, 0.7% with reservoirs, and 0.1% with railways." CN Waters and J Zalasiewicz, "Concrete: The Most Abundant Novel Rock Type of the Anthropocene," in *Encyclopedia of the Anthropocene,* ed. Michael I. Goldstein and Dominick A. Dellasala (San Diego: Elsevier, 2017), 80.

2 Throughout this analysis, my discussion of a cement's unique ability to alter environmental possibilities will be based on the concept of "possibilism" defined by Lucien Febvre and other geographers. It is the idea that human beings do determine the shape of their society, but only within the possibilities of the natural world. See: Lucien Febvre, *A Geographical Introduction to History*, trans. E. G. Mountford and J. H. Paxton (London: Alfred A. Knopf, 1925), 171-294.

Defining historical eras by their dominant materials is typically the role of antiquarians. The traditional three-part division of ancient history includes the Stone Age, Bronze Age and Iron Age. All had matured by the Common Era. Although human societies are still shaped by the materials that they use, there is no consensus regarding what is the most significant in contemporary societies. Some have suggested that the existing epoch is an Age of Steel.[3] Others have proposed that it is fossil fuels that are actually the driving force of modern industrial society.[4] The lifeblood of the modern world may very well be fossil fuels and the veins made of steel, but the body is of concrete. The modern stone is the most intensively utilized solid material on earth. Densely populated industrial cities depend on concrete's fire-resistant and waterproof qualities for buildings and infrastructure. Concrete foundations provide stable ground for building. Concrete infrastructure removes waste and deliver water as well as energy. Automobiles, airplanes and locomotives rely on transportation networks that are built of, or supported by, the gray matter. Even oil tankers and cargo ships set off and port on docks made of concrete. We are now in a Second Stone Age.

All concrete is an aggregate of cement, sand and gravel. Construction aggregates are naturally occurring, abundant and inorganic. Cement must be manufactured. For this reason, the deep history of cement production is crucial to understanding the origins of humanity's most recent megalithic monuments. The *longue durée* of cement production can be traced through the production of lime, cement's essential ingredient. This deep history is best imagined as a sort of punctuated equilibrium where technological stasis is

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3 Theodore A. Wertime, *The Coming of the Age of Steel* (Chicago: University of Chicago Press, 1962).

4 Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power* (New York: Free Press, 1992), 237.

interrupted with periodic, rapid and dramatic change occurring due to the congruence of particular material and cultural factors. *Homo sapiens* began burning calcium carbonate to produce lime for plasters around 12,000 years ago.[5] Although lime manufacturing has ancient and global roots, technological transitions that allowed for the sustained mass production of durable and waterproof cement have only occurred with the convergence of abundant fuels and raw material as well as robust building regimes and demand for large-scale construction on land and under water. Two such cement transitions created the modern concrete building regime. They can be imagined as the uneven pillars of a suspension bridge that spans from the Neolithic to our own epoch. If the suspension cable represents time and the amount of cement consumed represents elevation, one would start 12,000 years ago with the relatively small-scale use of lime plasters in the Levant, rise to the Roman concrete revolution, decline in the Middle Ages, begin to rise again in the Late Middle Ages and reach the second peak in the Industrial Age.

Each of this imaginary bridge's pillars were built in specific locations that provided the necessary materials for the sustained mass production of cement. Abundant supplies of calcium carbonate, fuel and sand are necessary for any large-scale building with cement. The sites of these two cement transitions—the Italian Peninsula and Great Britain—held such materials in abundance. Within these broad geographic areas, the zones of intensive cement production and consumption were also served by water communications, the most effective pre-industrial form of bulk transportation. Furthermore, the cultural conditions were met by maritime empires that accumulated

5 W. David Kingery, Pamela B Vandiver and Martha Prickett, "The Beginnings of Pyrotechnology, Part II: Production and Use of Lime and Gypsum Plaster in the Pre-Pottery Neolithic Near East," *Journal of Field Archaeology* 15, no. 2 (1988), 219-43.

materials and built into the sea. They differed in one significant regard. Thermal energy is an essential factor in the production of cement. In order to produce cement, calcium carbonate must be heated to at least 800-1000 degrees Celsius over an extended period of time. The ancient Roman cement manufacturers used organic fuels that included wood and charcoal to carry out this process. Roman cement kilns served as ovens that trapped heat and prevented overproduction, which sustained the intensive use of concrete for roughly four centuries. The supplies of organic fuels in the Mediterranean Basin were diminished at precisely the same time that imperial building demand declined, which makes it difficult to determine what exactly brought an end to the ancient Roman concrete building regime. Regardless of the cause of collapse, these ancient cement production methods persisted across the floodplain of the former Western Roman Empire with similar fuel sources and production technology for around two millennia.

Within this socio-technical milieu, the British substituted fossil fuels in the production of cement—thereby creating the first building material produced outside of the organic economy. This was possible due to a unique fossil endowment. It is well known that the isle of Great Britain contained large deposits of coal. Regions rich with fossil fuels existed in the north and the midlands, areas of intensive industrial development throughout the nineteenth century. Due to its relevance to industrial production, many environmental histories have been mined from these deposits. Few, however, consider the island's second fossil inheritance. Calcium carbonate—formed from fossilized marine organisms—also existed in large geological deposits. The entire London Basin, fed by northern coal since the Middle Ages, is built on chalk deposits that cradle the Thames River. British builders had exploited this unique geological inheritance to manufacture cement since at least the thirteenth century. This production system has largely been overlooked by historians as the necessary conditions for the British cement transition were not met until five centuries after the initial fusion of fossil fuels and fossil materials. Nevertheless, it began a process of building outside of the organic economy that has since transformed the world.

The Concrete Paradox

Hyperlithic building does not come without risks.[6] Wherever concrete is used to overcome environmental limits, the material simultaneously poses the threat of catastrophe. For example, concrete is the cheapest and most effective defense against the rising tides of a warming planet. The cement industry also contributes as much as 8% of greenhouse gas emissions through the burning of carbon trapped in fossil fuels and fossil materials.[7] This is not the only example of the concrete paradox. Dams are necessary for storing water and producing renewable energy. Yet, they have destroyed riparian ecosystems and development in flood zones of formerly free rivers are at risk of disastrous inundation. Dense urban settlement is made possible due to concrete's fire resistant properties and pipes made of the gray matter deliver water and remove sewage. Yet, crowd diseases continue to plague contemporary settled societies. Concrete ports, highways and runways deliver goods to our doorstep. They deliver pathogens as well.

With all of these threats to the modern lithic environment, it is surprising that today's *Homo habilis* is so confident. This arrogance is due to concrete lending itself to

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6 This is a portmanteau word that blends "hyper," implying excess, and "lithic."

7 Johanne Lehne and Felix Preston, "Chatham House Report: Making Concrete Change: Innovation in Low-carbon Cement and Concrete," *Chatham House, The Royal Institute of International Affairs,* June 13, 2018. Accessed May 3, 2021. https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete-0/executive-summary.

the perception of permanence and plenty. It delivers neither indefinitely. In a centennial history of portland cement, the industrial journalist Robert Lesley expressed his view of the permanence that the material conveys. “Cement means concrete; concrete means stone; and stone spells eternity, so far as our finite minds can comprehend,” he wrote in 1924.[8] It has been nearly another hundred years since Lesley’s claim. Closing in on the bicentennial of the invention of portland cement, concrete is still used to convey permanence. Cracks are already beginning to show. Infrastructure in the United States recently scored a dismal C- on the “Report Card for America’s Infrastructure” provided by the American Society of Civil Engineers. Modern concrete is largely to blame for the low score as twentieth century buildings that include freeways, runways, dams, buildings, schools, bridges and more are all starting to show the limits of the material.[9]

Modern concrete’s rather rapid rate of decay is due to reinforced concrete being a hybrid of steel and concrete. Twisted steel, known as rebar, gives reinforced concrete its strength. It is also susceptible to rust. Robert Courland described this existential threat, known to engineers as “concrete cancer.” “Not only is the amount of good ‘steel’ reduced,” wrote the popular historian of metallic decay through oxidation, “but the diameter of the rebar expands to as much as fourfold its original diameter, causing more cracks and, in due course, pushing out chunks of concrete.”[10] This limits the longevity of

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8 Robert Whitman Lesley, *History of the Portland Cement Industry in the United States* (New York: Arno Press, 1972), 3.

9 American Society of Civil Engineers, “2021 Report Card for America’s Infrastructure,” accessed, June 04, 2021, https://infrastructurereportcard.org/.

10 Robert Courland, *Concrete Planet : The Strange and Fascinating Story of the World's Most Common Man-made Material* (Amherst, N.Y.: Prometheus Books, 2011), 320.

reinforced concrete structures to roughly 50 to 150 years.[11] Contrast this with the Roman concrete monuments made with pozzolan cement that still persist, in some cases against the relentless forces of the sea, and one can perceive the issue. Concrete structures already built or those still on the architect's sketchpad will not last. No doubt there will be a layer of anthropogenic rock that baffles future paleontologists. Engineers, boosters and builders of the Second Stone Age did create something unique in human and geological history. The megalithic monuments of the Anthropocene will look nothing as they do today.

Although builders have long known of these limits to the eternal longevity of reinforced concrete structures, in some cases purposely ignoring this inconvenient truth, many still consider the material it is made from sustainable. In many ways they are correct. The modern industrial building transition resulted from the sustained mass production of structural materials. The production of modern concrete, as well as the iron/steel that strengthens structures made of it, have a relatively minimal impact on the biological world compared with their organic counterparts—timber in particular. Concrete has three essential ingredients: cement, sand and gravel. Sand and gravel, or construction aggregates, are the most heavily extracted raw materials on earth.[12] The necessary ingredients of modern cement are also bountiful. Calcium carbonate makes up roughly 4% of the earth's crust and exists on every continent in the form of limestone,

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11 Guy Keulemans, "The Problem with Reinforced Concrete," *The Conversation*, last modified June 17, 2016, accessed May 1, 2021, https://theconversation.com/the-problem-with-reinforced-concrete-56078.

12 Vince Beiser, "Why the World is Running Out of Sand," *BBC,* last modified 17 November, 2018, accessed May 3, 2021, https://www.bbc.com/future/article/20191108-why-the-world-is-running-out-of-sand.

chalk and marble.[13] Fossil fuels exist in similar abundance. This abundance has created and sustained the contemporary concrete cornucopia. One striking example of such plenty involves concrete construction in China where more cement was used between 2013 and 2015 than in the United States during the entire twentieth century.[14]

There are threats to the persistence of the Second Stone Age. Building from the stock has limits. Fossil fuels will not last forever. There is a chance that, if the world continues on its current energy path, the majority of fossil fuels will be depleted within this century.[15] If global warming is to be addressed, much less can be burned.[16] The cement industry is currently one of the most energy intensive industries in the world.[17] Modern cement, along with other thermal industries that include iron and steel, are largely produced with fossil fuels that superheat raw materials in ways that could not, in any significant manner, be transferred to organic fuel, hydro, solar or wind power. Alternative fuels such as solid waste and biomass account for as little as 6% of total fuel

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13 Industrial Minerals Association of North America, "What is Calcium Carbonate?," accessed June 4, 2021, https://www.ima-na.org/page/what_is_calcium_carb.

14 For an article on the modern cement boom, see: Ana Swanson, "How China used more cement in 3 years than the U.S. did in the entire 20th Century," *The Washington Post,* March 24, 2015, https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/.

15 Gioietta Kuo, "When Fossil Fuels Run Out, What Then?," *Millennium Alliance for Humanity and the Biosphere (MAHB),* last updated May 23, 2019, https://mahb.stanford.edu/library-item/fossil-fuels-run/.

16 A 2015 study argued that "over 80% of coal, 50% of gas and 30% of oil reserves are "unburnable" under the goal to limit global warming to no more than 2C." Helen Briggs, "Most Fossil Fuels 'Unburnable' Under 2C Climate Target, *BBC,* January 7, 2015, https://www.bbc.com/news/science-environment-30709211.

17 U.S. Energy Information Administration, "The Cement Industry is the Most Intensive of All Manufacturing Industries," last modified July 1, 2013, https://www.eia.gov/todayinenergy/detail.php?id=11911.

use in the cement industry.[18] Nuclear energy could power cement plants and melt stones, but facilities would need to be built or adapted to do so. No method could avoid the release of CO2 when calcium carbonate is burned. While politicians, endowed with a moral mission by the scientific establishment, push to find alternatives to fossil fuel use in the home, industrial and transport sectors, the cement industry has a long way to go.[19] Collapse of the concrete cornucopia has been kicked down the road, but will likely have a reckoning.

Cementation

Due to the centrality of cement to concrete production, the origins of the structures that contour the contemporary built world can be found in the deep history of the bonding agent. Definitions are a useful starting point for such an exploration. Cement is formed from lime produced by burning calcium carbonate at extremely high temperatures. It alone does not have the strength for large-scale structural uses and additives must be incorporated for strengthening purposes. With the addition of sand, cement becomes mortar. With the addition of sand and gravel, it forms concrete. Therefore, cement is upstream of each of these widely used building materials. Historical cement transitions can be identified by these materials' manipulations, of which there are two of central importance for this dissertation, "pozzolan cement" and "natural cement." Pozzolan cement is produced by adding volcanic sand to burnt lime in order to create a durable and waterproof cement. It was first incorporated into a large-scale building regime by the Romans around the dawn of the Common Era. Natural cement involved

18 "Cement," *International Energy Agency*, last modified June 2020, https://www.iea.org/reports/cement.

19 D.J. Barker, S.A. Turner, P.A. Napier-Moore, M. Clark and J.E. Davison, "CO2 Capture in the Cement Industry," *Energy Procedia* 1, no. 1 (2009), 87-94.

burning impure limestone rich in silica and alumina, a practice adopted in the Thames Basin at the close of the eighteenth century CE. These breakthroughs were separated by roughly two thousand years, but had many similar characteristics. Each created a durable and waterproof material. Each was adapted to building regimes with a variety of material inputs, divisions of labor and techniques for building on land and under water. Each were driven by the building demands of western maritime empires. Each significantly changed the environmental possibilities where the material was used.

Cement also has a dual meaning in the English language. It is used to connote a coming together and solidifying of things. This definition is also appropriate when considering the deep history of the bonding agent.[20] It would be too simple to claim that the abundant supplies of cement that are used today manifested when British innovators merged fossil fuels to fossil materials, thus creating a system to mass produce cement outside of the organic economy. In fact, this process had existed for half a millennium on the soggy island before the British achieved their own cement transition. It took another hundred years for natural cement to be supplanted by "portland cement," the most widely used cement today. That is because multiple necessary conditions must be met for a cement transition to occur. In particular, abundant fuels and raw materials in addition to robust building regimes and demand for large-scale building on land and under water are all required for significant building material transitions.

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20 Throughout the first two sections of this study, I will be using the *Long Durée*, or long view to describe the deep history of lime production and the use of volcanic sands to create hydraulic cement. For a description of Braudel's role in pioneering this approach, see: H. L. Wesseling and Eugen Joseph Weber, "Fernand Braudel: Historian of the "Long Durée," *Certain Ideas of France: Essays on French History and Civilization* (Westport: Greenwood Publishing Group, Incorporated, 2002), 167-181.

In order to explore the historical contingencies that led to the sustained mass production of inorganic cement and launched the modern lithic epoch, a brief historical overview of each factor that contributes to a cement transition is useful. The primary ingredient of cement is calcium carbonate. Its chemical makeup is $CaCO_3$ (one Calcium, one Carbon, and three Oxygen) and deposits can be found in many forms around the globe. Calcium carbonate is most abundant in the sedimentary rocks of limestone and chalk or the metamorphic stone marble. Marine organisms that include pearls, shells and coral reefs are also calcium carbonate based. In fact, most limestones and chalks are formed over millions of years from fossilized marine organisms. Calcium carbonate must undergo a transformation known as the "lime cycle" in order to be used as cement. By raising its temperature, heat drives out CO_2 and leaves quicklime, CaO. When water is added to quicklime, $Ca(OH)_2$ is created and hydrated, or 'slaked,' lime is produced. In the third phase of the lime cycle, slaked lime is exposed to the atmosphere where CO_2 is reintroduced as H_2O is driven off through evaporation. The chemical makeup of the material returns to $CaCO_3$ as the lime cycle is completed.[21] This process results in the desired bonding properties of cement.

Fuel is also required to carry out the lime cycle. Historically, fuels have included either organic sources in the form of wood and charcoal or fossil fuels. Organic fuels are limited to areas with an abundance of biological matter. They are susceptible to depletion whenever their use exceeds the regeneration cycle. Fossil, or mineral, fuels have different environmental dynamics. Like calcium carbonate deposits, they are stored in particular geological deposits. Also, like their fossil cousin, they often exist in abundance. Fossil

21 The British Lime Association, "Lime Cycle," accessed June 4, 2021, https://britishlime.org/education/lime_cycle.php.

fuel deposits are typically more capable of sustaining intensive energy regimes over long periods of time due to the copious amounts of energy that can be derived per unit. Unlike organic sources, they take millions of years to regenerate. Throughout their formation, CO_2 is trapped, which is released once these fuels are burned. Therefore, both fossil fuels and calcium carbonate emit significant amounts of CO_2 upon firing.

Slaked lime on its own would be a poor structural material. The addition of sand is needed to create mortar as well as concrete. These are inorganic substances that are abundant and found around the globe. Basically any sand could be used to produce mortars. However, in order to create a durable and waterproof cement, significant amounts of silica and alumina must be present.[22] The Romans accomplished this mixture with volcanic sands, or "pozzolans." By mixing together lime with these volcanic sands, the Romans created a compound of calcium-aluminum-silicates-hydrates (C-A-S-H).[23] This strengthened ancient Roman cement and allowed it to set under water in a process known as the pozzolanic cycle.[24] Pozzolan cement mixed with sand and gravel then allowed for building of large concrete structures like the Pantheon and hydraulic infrastructure that included docks, wharves and piers. The limit to this process involved such sands being confined to areas of volcanic activity. Endowed with an abundance of such materials, the Mediterranean Basin bloomed with ancient Roman structures made of pozzolan cement in the first centuries of the Common Era. It was not until the natural

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22 Marie D. Jackson, Sean R Mulcahy, Heng Chen, Yao Li, Qinfei Li, Piergiulio Cappelletti, and Hans-Rudolf Wenk, "Phillipsite and Al-Tobermorite Mineral Cements Produced through Low-Temperature Water-Rock Reactions in Roman Marine Concrete," *The American mineralogist* 102, no. 7 (2017): 1435.

23 Jackson et al., "Phillipsite," 1436-1437.

24 Charles Q. Choi, "Secrets of Longevity: Roman Concrete," *Inside Science*, accessed August 11, 2020, https://www.insidescience.org/news/secrets-longevity-roman-concrete.

cement transition in Great Britain that impure limestones called “septaria” were burned to the same effect, creating a “natural cement.” Shortly after, “portland cement”—a combination of calcium carbonate and sand fired at extremely high temperatures—replaced its industrial predecessor and sustained the cement industry of Great Britain. This is the material that is used around the world today.

Cement production also requires that all of the raw materials are brought together in a central production site. Within the ancient Mediterranean pyro-technological complex, kilns served as a sort of oven that provided the primary means for producing large amounts of cement in a central location over time. The Roman agriculturalist Cato the Elder was the first to pen a description of the lime kiln. He instructed his fellow property holders to build a “lime-kiln ten feet across, twenty feet from top to bottom, sloping the sides in to a width of three feet at the top…Be careful in the construction of the kiln; see that the grate covers the entire bottom of the kiln.”[25] This method paralleled open pit burning that was used around the world since ancient times and persisted well into the nineteenth century. Such static kilns provided an advantage because they trapped heat, thereby limiting the amount of fuels that were necessary to produce lime. This production technology served the same functions in ancient Rome and early modern London, which allowed for the sustained production of cement over centuries. Surprisingly, kiln technology changed little in the two thousand years between the height of these two imperial capitals. Well after the invention of portland cement in the mid-nineteenth century, the British still used similar kilns for cement production. Only late in

25 Cato the Elder, *De Agri Cultura* (London: Loeb Classical Library, 1934), Ch. 38, accessed June 4, 2021, https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Cato/De_Agricultura/A*.html.

the nineteenth century was the rotary kiln invented, which allowed for continuous construction in addition to adding oil and natural gas to the production fuel portfolio.

Moving raw materials to a central production site and delivering a finished product also requires bulk transportation. This too was similarly unchanged between the first and second cement transitions. Lime production is uniquely sensitive to transportation methods for two reasons. The fuel and raw materials necessary to create it are heavy and the finished product is susceptible to atmospheric and environmental ruin. Therefore, kilns were most advantageously located near sources of raw materials as well as large-scale construction sites. Prior to the Industrial Revolution, this situated nearly all significant cement works near population centers, often along water routes to import raw materials. Since the kilns required supplies of substantial amounts of fuel and raw materials, land transportation could not suffice for the mass production of cement. The finished product had additional transportation constraints. If pre-modern cement was exposed to the atmosphere or moisture, it clumped and ruined. Beyond being a heavy material needed in large quantities, lime burns exposed skin or, in the worst cases, caught fire or exploded. Due to each of these reasons, cement production was best located near sites of large-scale construction, primarily cities. It was due to these factors that ancient Roman and early modern British cement production/consumption zones were each in densely populated cities—Rome and London—served by rivers with access to the sea. Since these were each imperial metropoles, they also supplied the industry with the timber necessary for masonry forms, scaffolding and other features necessary for building with anthropogenic stones prior to the addition of reinforced steel in the second half of the nineteenth century CE. By then, railroads had changed the transportation possibilities of the cement industry—a transformation also enabled by cement's use in tunnels and bridges.

Demand for large-scale construction on land and in the water is the final necessary condition for cement transitions to occur. Had raw materials, kiln technology and bulk transportation routes been present without the techniques, labor organization and demand necessary for large-scale building on land and in the water, significant shifts in building material production would not manifest. There are two primary applications that have historically required large amounts of cheap, abundant, waterproof and fire-resistant building materials. The first involves dense urban settlement. Fire is a threat to all urban areas. Water delivery and sewage removal are also necessary for sustained settlement in densely populated cities. The ancient Romans and modern Britons used cement to create hospitable urban habitats made of brick and concrete buildings in addition to constructing urban hydraulic infrastructure.[26] It continues to serve these functions for the modern megacities of the twenty-first century.

The second intensive demand for cement includes transportation networks. Those reading this dissertation will recognize the importance of concrete to freeways and runways. These transportation routes have their own deep roots. Roman roads were known to include cements, or any available substitute. The British also used cement in road building and eventually for the grades, tunnels and bridges of the British railway system at home and abroad. Traditionally, however, cement was most significant for water transportation. Roman pozzolan cement proved a breakthrough in this regard. Not only could pozzolan cements set under water, seawater actually strengthens the mixture.

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26 Diane Favro, "'Pater Urbis': Augustus as City Father of Rome," *Journal of the Society of Architectural Historians* 51, no. 1 (1992), 61-84.

Beyond the well-known monuments of the Roman concrete revolution, the Romans shored up the seaborn empire with pozzolan cement in ports across the Mediterranean. Well into the nineteenth century, the British relied on pozzolan cement to rebuild the metropole of their own empire. The discovery of natural cement in Great Britain by the end of the eighteenth century upset this two-thousand year building tradition and provided a domestic substitute for British builders, which only intensified their own hydraulic building in ports and canals. This material was also used for industrial building projects around the world—most notably, the canal networks of the antebellum northern United States.

The Mix

In order to produce concrete, there are particular ratios of cement, sand and gravel that constitute "the mix." This dissertation has a mix of its own. It adds an academic environmental history to similar studies produced by popularizers, builders, architects, engineers and scientists while adding insights from academic environmental history and technology studies.[27] This is achieved through the utilization of concepts and methods from many different fields. Historical geography, technology transitions and the study of technology and culture are just a few academic disciplines that help explain the

27 There are many different works that fit into these categories. Popularizers include: Robert Courland, *Concrete Planet: The Strange and Fascinating Story of the World's Most Common Man-made Material* (Amherst, N.Y.: Prometheus Books, 2011) and G. M. Idorn, *Concrete Progress: From Antiquity to Third Millennium* (London: Thomas Telford, 1997); builders include: Charles Pasley, *Observations on Limes, Calcareous Cement, Mortars, Etc*. (London: J. Weale, 1838); architects include: Peter Collins, *Concrete: The Vision of a New Architecture*, 2nd ed. (Montreal: McGill-Queen's University Press, 2014) and Adrian Forty, *Concrete and Culture: A Material History* (London: Reaktion Books, 2013); engineers include: George R. Burnell, *Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering, Etc.* 5th ed. (London: C. Lockwood & Son, 1900) and A.J. Francis, *Cement Industry 1796-1914* (Devon, UK: David and Charles Publishers, 1978); scientific approaches include *Lea's Chemistry of Cement and Concrete*, 5th ed., ed. Peter Hewlett and Martin Liska (Oxford, UK: Butterford-Heinemann, 2019) and Amy E. Slayton, *Reinforced concrete and the modernization of American Building, 1900-1930* (Baltimore: Johns Hopkins University Press, 2001).

conditions from which cement transitions emerge and how they change the environments and societies where they occur. This dissertation also posits that modern cement production played a significant role in global history as it was used for imperial and industrial purposes.[28] In its most comprehensive form, this dissertation seeks to demonstrate the origins of modern concrete lock-in through the cement transitions of the late eighteenth and early nineteenth centuries.

Historical geography provides a guide for such a task as one must consider the environments where cement transitions occur, where cement technologies spread and how environments and societies are transformed by the material. Specifically, this dissertation is built around the concept of possibilism.[29] This hypothesis proposes that social customs, norms and practices are formed by people, but shaped by the possibilities afforded by the environment. For instance, there are many different cultures that have developed in highland regions, none of which are seafaring cultures. By acknowledging human agency in shaping the structure of societies as well as environmental factors, possibilism provides a method for avoiding the pitfalls of cultural and environmental determinism. Since anthropogenic stones have become the primary means of manipulating environmental possibilities, the following environmental history of cement also stresses the impact of the transformation of the built world on particular societies. Cement transitions can be thought of as initiating feedback loops where the mass

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28 Some examples include: William McNeill, *The Rise of the West: A History of the Human Community* (Chicago: University of Chicago Press, 1992); Robert Marks, *The Origins of the Modern World: a Global and Ecological Narrative* (Lanham, Md.;: Rowman & Littlefield, 2007); and Kenneth Pomeranz, *The Great Divergence: China, Europe, and the Making of the Modern World Economy* (Princeton: Princeton University Press, 2000).

29 Febvre. *A Geographical Introduction*, 171-294.

production of the bonding agent changes human geography—a process that requires the continued manufacturing of cement.

In the age of digital technology, it may seem strange to think of the cold concrete beneath one's feet as technology.[30] That is precisely what concrete is. For this reason, methods borrowed from technology and culture studies offer useful perspectives for exploring the development of cement production systems and the application of the building materials that they facilitate. Broadly conceived, as historian Rudi Volti succinctly described, technology is understood in this system as "a system created by humans that uses knowledge and organization to produce objects and techniques for the attainment of specific goals."[31] Surprisingly little changed with the physical artifact of the cement kiln in the two thousand years after the Roman cement transition. Methods of firing, materials and the application of the finished material did. By understanding technology in this broadest scope, one can see that the production and application of cement is influenced by a multiplicity of cultural and material factors.

Since this dissertation fundamentally considers change over time, technology transitions are also useful for such an examination. There are many different ways to define technology transitions. In *Technological Change and the British Iron Industry,* Charles K. Hyde proposed that the British iron industry underwent a technological transition once 90% of the manufacturers had switched to coal.[32] This dissertation does

30 This perspective was cultivated through reading: David Edgerton, *The Shock of the Old* (Oxford: Oxford University Press, 2007).

31 Rudi Volti, *Society and Technological Change*, 6th ed. (New York: Worth Publishers, 2008), 6.

32 Charles K. Hyde, *Technological Change and the British Iron Industry, 1700-1870* (Princeton, N.J: Princeton University Press, 1977), 196.

not take such a rigid approach. It defines cement transitions as occurring whenever the production process and properties of cement are altered in a way that significantly changes construction possibilities. In order to explore such transformations, the multi-level perspective (MLP) pioneered by Richard Geels proved informative.[33] MLP acknowledges innovations/innovators, dominant technological regimes, the role of emergent technologies in changing those systems and technological lock-in. Each of these concepts are useful for considering cement transitions and their associated impact on the built world. Thomas Hughes' *Networks of Power* also served to develop this examination through the concepts of "reverse salients," "technology transfer" and "technological momentum" as each were factors that shaped cement transitions and determined where they spread.[34] As is true of most large-scale technological systems, different cement technologies emerged, individuals were habituated to the material's use, substitutes gradually replaced their predecessors and, once adopted, created path dependencies.

When paired with the concept of possibilism, the environmental factors for such changes are foregrounded. Due to this focus, this dissertation parallels energy studies that have offered ample examples of the connection between geological resources and contemporary industrial society. For instance, E. A. Wrigley's distinction between the organic and mineral economy contrasted energy regimes in relation to organic or mineral

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33 There are many different frameworks for understanding technology transitions. This dissertation adopted the Multi-Level Perspective. See: Frank W. Geels, "Ontologies, Socio-technical Transitions (to Sustainability), and the Multi-level Perspective," *Research Policy* 39, no. 4 (2010), 495-510 and Frank W. Geels, "Technological Transitions as Evolutionary Reconfiguration Processes: a Multi-Level Perspective and a Case-Study." *Research policy* 31, no. 8 (2002): 1257–1274.

34 Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins University Press, 1983).

energy sources.[35] In "organic economies," all acts of thermal production were carried out with biofuels. Mineral economies, on the other hand, were those that exploited fossil fuels. Drawing energy from the stock allowed for short term gain as fossilized carbon was exploited and, as Wrigley noted, has since sustained modern demographic and industrial growth.[36] The same framework can be applied to construction. Building from the flow conditioned what was possible throughout much of human history. This involved the use of timber, primarily, for structural as well as energy purposes. Even calcium carbonate, coal's fossil cousin, was burned with organic fuels thereby placing most pre-modern cement regimes firmly within the organic economy. The fusion of fossil fuels and fossil materials in Great Britain allowed for the production of cement from the stock alone. Although the material was outside of the organic economy, building still required wood frames, foundations, posts and other organic inputs. Only with the advent of natural cement did building from the stock develop and spread around the world.

A final consideration involves examining the social and ecological consequences of cement transitions. In *Power to the People*, historian Paul Warde and his co-authors use the term "development blocks" to define "the series of systems of technology, infrastructure, energy sources, and institutions by which economic growth proceeded."[37] Warde et al. recognized, as did many others, that coal, steam and iron were the crucial

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35 E. A. Wrigley, *Continuity, Chance & Change: The Character of the Industrial Revolution in England* (Cambridge, UK: Cambridge University Press, 1988).

36 E. A. Wrigley, *The Path to Sustained Growth: England's Transition from an Organic Economy to an Industrial Revolution* (Cambridge, UK: Cambridge University Press, 2016).

37 Astrid Kander, Paolo Malanima, and Paul Warde, *Power to the People: Energy in Europe over the Last Five Centuries* (Princeton: Princeton University Press, 2014), 8.

features of the industrial development block.[38] This dissertation argues that the ability to access abundant mineral cement is a central feature of the development block. For the reasons outlined above, fire-resistant and waterproof concrete is also essential for industrial take-off. Due to being a bulk material needed in large quantities for concrete building, each modern developed region relies on abundant supplies of cement that could not be produced on such a scale with organic fuel. Therefore, a history of cement ought to be understood as a necessary feature of any "developed" society of the Industrial Age. Once a particular region is transformed by access to abundant supplies of cement, the social dimensions are transformed into what could be considered "cement societies." William Cronon's "second nature" or Carolyn Merchant's "ecological revolutions" are two examples of the relation between the social impacts of changing environments that inform this dissertation's understanding of the cement development block.[39]

Frames

When possibilism, the cultural dimensions of technology and technology transitions are paired to explore the history of cement, it demonstrates that contemporary cement production systems constitute a unique technology that has significantly altered environments and societies around the world. This dissertation considers the origins of this technology by exploring the deep history of cement and the material's role in early nineteenth century industrialization. Generally, historians overlook cement in such

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38 Robert Marks, *The Origins of the Modern World: a Global and Ecological Narrative* (Lanham, Md.;: Rowman & Littlefield, 2007), 113-114.

39 Cronon's "Second Nature" is described in *Nature's Metropolis: Chicago and the Great West* . 1st ed. (New York: W. W. Norton, 1991), 62. Merchant defines such ecological revolutions as processes that "altered the local ecology, human society, and human consciousness." Carolyn Merchant, *Ecological Revolutions: Nature, Gender, and Science in New England* (Chapel Hill: University of North Carolina Press, 2010), 3.

examinations. For instance, in a staple history of the Industrial Revolution, historian David Landes devotes three lines out of three hundred pages to cement. He writes that the nineteenth century is less significant for historical examination of concrete as "the great days of rubber and cement, for example, still lay in the future."[40] He may be correct when considering the "indirect savings" and "derived demand" of the concrete industry. He is wrong, as this dissertation will show, about the impact of cement on large-scale infrastructure. Before the fire-prone steam engines could be used in densely populated industrial cities, cement created fire-resistant habitats. These industrial zones were provided with bulk materials by canals made of cement. Global trade was supported on docks, harbors and other infrastructure of maritime empire made of cement. Steam engines moved across continents and through mountains with bridges and tunnels made of cement. Eventually, steam ships moved along the canals and moored to docks made of cement. The following pages provide an environmental history of this foundational material to the modern world.

All construction projects that use cement require frames to mold the material to desired ends and to support the final structure. This dissertation also needed frames. In order to provide such structure, the chapter titles are organized around the three necessary inputs for producing cement and its final product. They create a framework for understanding the origins of the contemporary concrete cornucopia. Chapter 1, "Sand," applies the *longue durée* to describe the two material developments that led to the modern cement regime. The ancient Roman pozzolan cement transition afforded a durable and

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40 David S. Landes, *The Unbound Prometheus: Technical Change and Industrial Development in Western Europe from 1750 to the Present*, 2nd ed. (Cambridge, UK; New York: Cambridge University Press, 2003), 299.

abundant alternative to earlier cement mixtures allowing for the material's structural application on land and in the Mediterranean Sea. Although the ancient Roman cement regime collapsed along with the empire—possibly due to biological fuel limits in the Mediterranean Basin—the methods for the production of pozzolan cement persisted across western Europe until the Industrial Revolution. The pozzolan cement transition shaped the possibilities of building with artificial stones for thousands of years and provided the socio-technical milieu from which the modern cement transition emerged.

"Lime," the title of the second chapter, is the second essential ingredient of cement. This material is produce by applying heat to calcium carbonate over an extended period of time. *Homo sapiens* have been producing this material for roughly 12,000 years. For much of that history, organic fuels were used to fire calcium carbonate. British lime burners upset that tradition by burning calcium carbonate with fossil fuels, both abundant materials on the island of Great Britain, beginning in earnest by the thirteenth century. This created a material that was produced outside of the organic economy, which had significant impacts on British society since its invention. The material was used in urban building and as an agricultural supplement, which helped the British avoid Malthusian 'positive checks' related to building, food and clothing in the centuries leading up to the Industrial Revolution. British urbanization between 1600 and 1800 avoided interruption despite environmental disadvantages related to limited land mass, poor climate, damp soils, catastrophic events like the Great Fire of London in 1666 and periodic building timber shortages. Although London emerged as the largest western European city by the early nineteenth century, brick and mortar building, dominant in the building regime of London, remained low quality due to the mortars that were haphazardly burned with coal in large quantities. Although solutions to the low quality mortars were suggested by the scientifically minded by the end of the eighteenth century, they required slowing and refining production of the essential building material. Such suggestions were never adopted. The city's lime burners persisted in their practice of rapidly burning Thames chalk with fossil fuels. The lowly lime burners and brick layers of London had realized something that few others did then or since, the quantity of cement has a quality all its own.

"Water," serves as the third chapter title. In the process of making cement, H_2O is added to heated lime in order to dissolve the matter into paste and activate the bonding qualities of lime. It also provides a useful organizing theme for examining the use of cement to shore up the metropole of the global British Empire. Kenneth Pomeranz proposed that a British 'great divergence' began in the early nineteenth century due to "coal and colonies" providing the means for industrial growth and related economic gains.[41] Although many historians adhere to Pomeranz' formula, many others have identified British industrial and imperial take-off as starting around 1760. Such drivers of industrial change include iron production, technological innovations and the spread of steam engines to name a few. This chapter expands on Pomeranz' framework and adds cement as a material that grew in significance from the mid-eighteenth century forward. Although remaining within the pozzolan cement tradition, the British engineer John Smeaton discovered the hydraulic properties of impure calcium carbonate in the 1750s and used it extensively in hydraulic works throughout his lifetime. The mixture of pozzolan sand and impure limestone was widely adopted for such construction shortly

41 Pomeranz, *The Great Divergence.*

after its discovery and used extensively over the next one hundred years for building projects that included lighthouses, bridges, docks and other structures that modernized the Port of London as well as the canals that connected industrial centers to the hinterlands that fed them. All were employed for the secure and rapid movement of colonial goods and bulk materials that included coal. Through exploring cement as foundational to British imperial consolidation and industrial growth, this dissertation adds another "c" to the drivers of the British great divergence.

"Cement," the final chapter, considers the British natural cement transition. This began at the turn of the nineteenth century when the cementitious properties of septaria stones were found to create a durable, hydraulic and quick-setting cement by Dr. Rev. Samuel Parker who lodged a patent for "Roman cement" in 1796. Ironically named after the ancient material that it superseded, this material soon replaced pozzolan cement in building on land and under water. No longer requiring imports of sand, British natural cement provided an abundant supply of durable, waterproof and fast-setting cement that remained free from the organic economy. This greatly expanded the building possibilities of the island related to hydraulic building, urban construction and transportation. It also freed the zones of intensive cement production and consumption from western Europe. Similar natural cement systems were soon discovered and exploited in other industrial regions around the world—most notably the antebellum United States where it was used to build the early national canal systems of the antebellum north. This was an early example of the technological diffusion that has since transformed the world.

By the end of the nineteenth century, the modern cement production system had reached technological momentum with the invention of portland cement—a mixture of sand and calcium carbonate fired at extremely high temperatures—and the rotary kiln.[42] This increased the volume of production and expanded the areas where the material could be produced. As the concluding chapter title suggests, it was a crucial factor in "Sustaining the Second Stone Age." The portland cement regime grew from a process set in motion between roughly 1750 and 1850. Since then, cement production and use has reached geologic proportions. The concrete paradox persists and in order to explore the costs and benefits of megalithic building with anthropogenic stones, it is useful to consider its history. Understanding the roots of the concrete cornucopia provides a starting point for seriously considering the possibilities and limits of the Second Stone Age.

42 Hughes, *Networks of Power,* 140-174.

CHAPTER TWO

SAND

Introduction

Augustus, the first emperor of Rome (27 B.C.E.-14 C.E.), reportedly claimed that "he entered the city of Bricks and left it a city of marble."[43] The quote has been oft-repeated as it reflects both the physical rebuilding of the city and the power of the Roman Empire. In each case, calcium carbonate would have been a better descriptor. Marble monuments were far less prevalent than the cement buildings, concrete monuments and infrastructure in the city. Many ports of the empire were built with Roman cement mixtures that withstood the force of the sea. All of which was possible due to the materials, organization and techniques afforded by the imperial building regime. The ancient Roman cement transition and subsequent Roman concrete revolution both symbolized the ascendancy of the empire and allowed it to take the form that it did. Unbeknownst to Augustus, building with calcium carbonate also demonstrated the limits to empire. Just as anthropogenic stone is not as durable as its natural counterpart, the empire cracked and eventually crumbled. Nevertheless, the collapsing structures of the Western Roman Empire served as inspiration for the cement producers of Western Europe who maintained the ancient tradition for nearly two millennia. Published in 1753, Belidor's *Architecture Hydraulique* was similar in its prescriptions for hydraulic cement

43 Diane Favro, "'Pater Urbis': Augustus as City Father of Rome." *Journal of the Society of Architectural Historians* 51, no. 1 (1992): 61.

as Vitruvius' account of ancient Roman mixtures.[44] The modern cement transition emerged from an ancient Roman inheritance.

The *longue durée* of lime—cement's essential ingredient—production in western Europe is an ancient story that reaches further back in time than the Roman imperial moment. Manufacturing lime is one of humanity's oldest thermal industry, predating the smelting of metals by roughly 6000 years.[45] The earliest evidence of lime burning can be found at the moment that human beings began to live in settled societies. Lime's use as a plaster can be traced back to the Levant around 12,000 years ago.[46] Also unlike metals, the production of lime was a global phenomenon practiced by socially stratified societies in the Americas as well.[47] The sustained mass production of abundant supplies of durable and hydraulic cement for structural purposes only emerged in the highly stratified societies that could marshal the materials, fuels, techniques, coerced labor and finances necessary for large-scale building on land and in the water. It took roughly ten thousand years from lime's first production in the Mediterranean for these conditions to be met by the ancient Roman Empire.[48] The Romans elevated lime production to a position in a building regime that was unique in world history.

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44 Belidor, *Architecture Hydraulique*.

45 Theodore Wertime, "The Furnace Versus the Goat: The Pyrotechnologic Industries and Mediterranean Deforestation in Antiquity," in *Journal of Field Archaeology,* 10, no. 4 (Winter, 1983), 447.

46 W. David Kingery, Pamela B Vandiver and Martha Prickett, "The Beginnings of Pyrotechnology, Part II: Production and Use of Lime and Gypsum Plaster in the Pre-Pottery Neolithic Near East," *Journal of Field Archaeology* 15, no. 2 (1988): 219-43.

47 D. Clark Wernecke, "A Burning Question: Maya Lime Technology and the Maya Forest," *Journal of Ethnobiology* 28, no. 2 (Fall/Winter 2008): 200-210.

48 Gilberto Artioli, Michele Secco and Anna Addis, "The Vitruvian Legacy: Mortars and Binders Before and After the Roman World," *EMU Notes in Mineralogy* 20 (2019): 167.

Although the Romans were the first to wed durable and waterproof cement to a cohesive building regime, all lime manufacturers throughout time grappled with the same production constraints. The environmental dynamics of lime production are best understood through the concept of organic economies proposed by historian E.A. Wrigley.[49] He explained, "plant photosynthesis was at the base of all productive activity in organic economies."[50] In relation to thermal industries, this was due to the use of firewood, charcoal or peat. These fuel types were renewable, but would take years, if not decades, to regenerate once exhausted. They were also limited to forests, fields and bogs where organic fuels were plentiful. All organic economies were thus confined by the trade-offs associated with land. For instance, any increase in land set aside for firewood would reduce the amount of land allocated to agriculture and vice-versa.

A similar framework can be applied to building materials. Building timber would also require land to grow and therefore was directly related to the limits of the organic economy. Prior to the Industrial Age, nearly all synthetic construction materials were connected to the organic economy through a reliance on biofuels in manufacturing as well. Thermal production of limes, metals and terra cottas may seem inorganic, but still relied on abundant supplies of firewood to create. In these industries, the three variables of fuel, raw materials and pyro technology formed a sort of production triangle. Raw materials and fuel can be envisioned as the first two points of this imaginary shape. Metals that include bronze and iron share the greatest similarity to lime production because they are made from abundant and inorganic raw materials. Just as coal fuel exist

49 E. A. Wrigley, *Continuity, Chance & Change*.

50 E. A. Wrigley, *The Path to Sustained Growth,* 9.

as stocks in the earth's crust, calcium carbonate, copper, tin and iron-ore maintain similar qualities. For instance, iron-ore and calcium carbonate each exist in abundance around the world, both making up roughly 4% of the earth's crust.[51] With the notable exception of lime production in Great Britain from the thirteenth century forward, converting these mineral resources into materials was done with biofuel. Therefore, although the raw materials to produce such materials were abundant and inorganic, the reliance on biofuels placed their production firmly within the organic economy.

The cement transition of the Roman Empire was carried out in such an organic building regime. Although the material itself changed little after the rise of the Roman Empire, its production was fused to a robust Roman building regime and accelerated to serve the building demands of maritime empire. "Nowhere else in the world, not even in China," observed archeologist Theodore Wertime, "did iron-steel, glass, terra cottas, and cement take on the synergistic power achieved in the building of Greco-Roman civilization."[52] This was largely possible due to the developed thermal industries that existed at the time. Various thermal developments had occurred in the Mediterranean World by the time of Augustus' rise to power. Imperial Roman cement was used in this socio-technical context for large-scale masonry and concrete building on land and under water.[53] This deserves contrasting with the Chinese example. Lime producing technologies were known in China at the time of the Roman imperial building regime.

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51 Industrial Minerals Association of North America, "What is Calcium Carbonate?"

52 Wertime, "The Furnace Versus the Goat," 449.

53 Artioli et al. found that Roman uses included the "first fully recorded structural use of binders in architecture, in which the binder intimately links the units of the masonry and actively contributes to the mechanical strength of the composite structure." Artioli et al., "The Vitruvian Legacy," 172.

Chinese builders were also accomplished in masonry building and the construction of hydraulic works as well as monumental buildings. Why then, did the Roman imperial builders accomplish the only concrete revolution in ancient history?

It had a lot to do with luck. Massive deposits of pozzolans were literally under the sandals of Roman builders. These deposits strengthened and waterproofed cement. They also had little risk of overexploitation. Only recently have historians given due attention to this important material fortune.[54] The lag in scholarship is partially the result of seeing cataclysmic events as such. Notoriously, the eruption of Mt. Vesuvius covered the city of Pompeii with volcanic sands. This terrible event remains prominent in the imaginations of historians. In the case of pozzolan cement, the tumultuous nature of the Mediterranean volcanic zone actually proved beneficial to builders. The Roman architect Vitruvius described the properties of the sands similar to those that encased the denizens of Pompeii where they slept. He explained that pozzolan sand was "a kind of powder which from natural causes produces astonishing results. It is found in the neighborhood of Baiae and in the country belonging to the towns round about Mt. Vesuvius."[55] Even before the eruption that buried Pompeii, Vitruvius suspected the volcanic origins as "in ancient times the tides of heat, swelling and overflowing from under Mt. Vesuvius, vomited forth fire from the mountain upon the neighboring country."[56] Volcanoes destroyed ancient

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54 See: C. J. Brandon, R. L. Hohlfelder, M.D. Jackson, and J.P. Olsen, *Building for Eternity: The History and Technology of Roman Concrete Engineering in the Sea* (Havertown: Oxbow Books, 2014).

55 Vitruvius Pollio, *The Ten Books on Architecture*, trans. Morris Hickey Morgan (Harvard: Harvard Univ. Press, 1914), 46.

56 Vitruvius, *The Ten Books*, 47.

cities and civilizations in the Mediterranean World, but they also deposited seemingly endless supplies of the valuable resources.

In fact, volcanic sands fit for use as pozzolans existed across the Mediterranean Basin. This was the only heavily populated region in the Eastern Hemisphere during the Axial Age with such abundance. A contrasting example can be seen with Chinese builders, hundreds of years later, during the Ming Dynasty. Similar to their ancient Roman counterpart, the Chinese state had the techniques, labor and financial resources for large-scale building on land and under water. Notoriously, Ming builders cleared the Grand Canal and promoted sea travel following the collapse of Mongol rule. Without ready access to pozzolans, these builders resorted to organic additives to strengthen cement. Seemingly originating with tombs in the Song Dynasty and continuing to be used in walls, most notably the Ming Wall of China, sticky rice was added to hydrated lime to form a durable "organic mortar."[57] This organic substitute for pozzolans had a similar strengthening effect. However, it amplified the trade-offs associated with producing cement in the organic economy as firewood and agricultural surplus were each necessary ingredients. Pozzolan cement differed from its Chinese counterpart as it was an "inorganic mortar" made from abundant and inorganic additives.

The term "inorganic mortar" is misleading, however. It implies that the Roman mixtures were not bound to the biological world. Although pozzolan sand provided abundant inorganic materials to strengthen mortars, the cement was still produced with organic fuels. In fact, all of the Roman thermal industries relied on biofuel, often in the form of wood or charcoal. In both the Chinese and Roman cases, fuel for producing

57 Yang, Fuwei, Bingjian Zhang, and Qinglin Ma, "Study of Sticky Rice–Lime Mortar Technology for the Restoration of Historical Masonry Construction." *Accounts of chemical research* 43, no. 6 (2010), 937.

cement competed with the agriculture needed to sustain populations or, in the case of the Ming Dynasty, for cement production. In the Roman case, this could have contributed to the collapse of their building regime. The most well-known causal factor of the waning of Roman concrete building involved the lack of investment for large-scale construction.[58] Roman investments declined considerably by the third century C.E., which left domestic infrastructure to crumble, a pattern long proved true of empires. A second significant factor of decline was environmental. The downfall of the Roman building regime occurred at precisely the same time that widespread deforestation due to the spread of the *Latifundia* slave agriculture system and consumption of timbers for fuel and building demonstrated the organic limits in the Mediterranean Basin. Historian John McNeill noted that, "by the time the Roman Empire began to totter it is likely that no extensive forest remained in the plains or low hills surrounding the Mediterranean."[59]

Collapse would be too strong of a word to describe the decline of the Roman building regime, however. The techniques of the ancient Roman cement production system were maintained across the regions of the former Western Roman Empire for millennia, albeit on a much smaller scale. For roughly four centuries, the Romans had demonstrated the promise of sustained production of anthropogenic stones for serving two necessities of maritime empires—large-scale urban building and hydraulic

58 P.J. Heather, *The Fall of the Roman Empire a New History of Rome and the Barbarians* (New York ;: Oxford University Press, 2010).

59 J. R. McNeill, *The Mountains of the Mediterranean World: An Environmental History* (Cambridge: Cambridge University Press, 2003), 72-73.

construction.[60] Not surprisingly, the achievement of ancient Roman builders provided inspiration across western Europe well into the nineteenth century. Production of such materials increased in the Late Middle Ages as the European states began their long consolidation of power after the Great Plague. Their building methods and materials changed little. Belidor's 1753 treatise was not the only one that echoed the past. Leon Battista Alberti's treatise *The Art of Building in Ten Books,* first printed in Florence in 1485, differed little from Vitruvius' *Ten Books on Architecture* written in the last decades before the Common Era.[61] Biringuccio was the Renaissance writer to describe thermal industries in *Pirotechnia* first published in Venice in 1540.[62] His description was nearly identical to Cato the Elder who described Roman lime kilns seventeen centuries earlier.[63]

This chapter proposes that although the ancient Roman cement transition and associated concrete revolution dwindled, the methods and applications persisted across western Europe for roughly two thousand years. Building possibilities in this western European building regime were determined by inherited knowledge, the environmental dynamics of thermal industrial production in the organic economy and the supply of sand. Pozzolan sands provided Roman builders, and those across western Europe for millennia, an abundant and inorganic strengthening agent for durable and waterproof cement. These

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60 K.D. White states, "Faventinus (fourth century) and Palladius (perhaps a half century later) belong to a period when the great age of imperial concrete structures was already at an end," K.D. White, Greek and Roman Technology (Ithaca, N.Y.: Cornell University Press, 1984), 85.

61 Leon Battista Alberti, *On the Art of Building in Ten Books,* trans. Joseph Rykwert, Neil Leach, and Robert Tavenor (London: MIT Press, 1988); Vitruvius, *Ten Books.*

62 Vannoccio Biringuccio, *The Pirotechnia of Vannoccio Biringuccio: The Classic Sixteenth-Century Treatise on Metals and Metallurgy*, trans. Cyril Stanley Smith and Martha Teach Gnudi (New York: Dover Publications, 1990).

63 Cato the Elder, *De Agri Cultura*, Ch. 38.

“inorganic mortars” were actually organic cements, tied to the biological world due to the need for organic fuels.[64] As advanced as the Roman cement production regime and its successors were, the western European building regime never escaped the environmental limits of the organic economy. It did create a socio-technical cement production system from which the modern concrete world emerged.

Ancient Origins

Indeed, the first cement transition owed much to the Roman Goddess of *Fortuna*. She represented good fortune and was often depicted holding a cornucopia in one hand with a ship’s rudder in the other while standing on a ball that represents uncertainty. *Fortuna* gifted a geographic endowment to the Romans, abundant amounts of pozzolan sand. With this essential ingredient of Roman cement, the bonding agent lent itself to durable, waterproof and fire-resistant building. Pozzolan cement was the final material addition to a pyro-technological complex long in the making. By the second century B.C.E., Pozzolan cement was used, more than any other material, to expand the possibilities of building in the ancient world. Monuments that include the Coliseum and Pantheon are the most visible examples of the success of this ancient Roman cement transition, but pozzolan cement proved transformative for maritime building as well.

A greater understanding of this unique Roman contribution to the history of building materials can be accomplished through a brief global survey of the material possibilities of the ancient world. When considered in relation to other densely populated regions with monumental construction, the Romans stand out for two reasons. The first

64 Italy relied on firewood and charcoal until the nineteenth century. Warde et al., *Power to the People,* 113.

involved the unique technological complex of the Mediterranean World. Archaeologist Thoedore Wertime described this socio-technical milieu by observing that, "iron, glass and cement trace their origins to the development of a common furnace-kilning technology in the ancient Mediterranean—Middle East…such a technology was not entirely duplicated anywhere else in the world."[65] He continued, "although the kilns or furnaces may have come from widely separated sources (the pottery kiln from the cooking hearth and the lime kiln from the fire setting of stone, for example), what emerged during the Bronze Age were four major interwoven pyrotechnological products. They were terra-cottas, iron, glass, and cement."[66] With the addition of pozzolan cement, the Romans enabled the large-scale use of other structural materials that included fired brick as well as concrete.[67] The second unique feature of the Roman cement regime was the abundance afforded by volcanic sand. The *longue durée* of thermal industries related to settled societies of the Mediterranean World demonstrated the global historical significance of each of these factors which allowed the Romans to undergo the first cement transition in history.

The story of lime burning and use in the Near East began much earlier. Throughout the pre-pottery Neolithic period, roughly 12,000 to 7,000 BCE, a lime burning technological complex existed across the Levant that demonstrated advanced skill and craftsmanship.[68] Although there were likely multiple different technological

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65 Theodore Wertime, *Coming of the Age of Iron* (Yale: Yale University Press, 1980), 7.

66 Wertime, *Coming of the Age*, 7.

67 Cato the Elder included discussions of walls and foundations made of such materials in *De Agri Cultura,* ~160 BCE. Cato the Elder, *De Agri Cultura*, Ch. 38.

68 Kingery et al., "The Beginnings," 220.

dawns related to making lime around the world, manufacturing lime in the Mediterranean World likely originated in the ancient Near East around 12,000 years ago.[69] It is made by burning calcium carbonate, which is most abundantly found in sedimentary rock layers of limestone, chalk and marble.[70] Many of these deposits begin as sheets of fossilized seashells and coral reefs formed in warm and shallow water. Thus, much of calcium carbonate is similar to coal due to each being carbon based and formed over geological time spans. As is true with all carbon based rocks, photosynthesis creates them, time fossilizes them, plate tectonics move them, and the earth often conceals them. Since ours is a marine planet, these deposits can be found on every continent. The ancient building sites of the Near East were built atop calcium carbonate deposits in the form of limestone. Even the earliest human settlements show signs of the material's use as Göbekli Tepe, the oldest of such settlements in present day Turkey, is known for its large T-shaped limestone pillars mined from the calcium carbonate in the region.[71] Lime manufacturing was also a global phenomenon in the ancient world, used across India, China and Mesoamerica.[72]

Little is known about the origins of this ancient industry, however. Wertime hypothesized that the practice of burning limestone developed at the quarry where fire

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69 Kingery et al., "The Beginnings," 220.

70 James S. Monroe, *The Changing Earth: Exploring Geology and Evolution,* 5th ed. (Boston, MA: Cengage Learning, 2008), 61.

71 "Göbekli Tepe," *World History Encyclopedia,* accessed June 4, 2021, https://www.worldhistory.org/G%C3%B6bekli_Tepe/.

72 Seligson, Kenneth, Tomás Gallareta Negrón, Rossana May Ciau and George J Bey, "Burnt Lime Production and the Pre-Columbian Maya Socio-Economy: A Case Study from the Northern Yucatán," *Journal of anthropological archaeology* 48 (2017), 281–294. See also: Altorio et al., "The Vitruvian Legacy."

was used for rock setting.[73] Another possible origin could have been from the hearth as pouring water on hot calcium carbonate may have revealed the mysterious properties of lime.[74] Regardless of origins, it is clear that, second only to firing ceramics, producing lime for plaster and putty is one of the oldest thermal industries. The shift from smashing, chipping and flaking stones to using heat to transform them was a significant technological transition in human history.[75] Today, scientists refer to this conversion of calcium carbonate to lime by the application of heat and water as the lime cycle, which has three stages. The first step involves burning calcium carbonate at temperatures of around 800-1000 degrees Celsius in order to release CO_2 and create quicklime.[76] Water is then added, which forms a putty known colloquially as "slaked lime."[77] Finally, the

73 Wertime, *Coming of the Age of Iron,* 8.

74 St. Augustine marveled at this process when he wrote, "Let us consider the wonders of lime; for besides growing white in fire, which makes other things black, it has also a mysterious property of conceiving fire within it. Itself cold to the touch, it yet has a hidden store of fire, which is not at once apparent to our senses, but which experience teaches us, lies as it were slumbering within it even while unseen. And it is for this reason called "quicklime," even as if the fire were the invisible soul quickening the visible substance or body. But the marvelous thing is, that this fire is kindled when it is extinguished. For to disengage the hidden fire the lime is moistened or drenched with water, and then though it be cold before, it becomes hot by that very application which cools what is hot. As if the fire were departing from the lime and breathing its last, it no longer lies hid, but appears; and then the lime lying in the coldness of death cannot be re-quickened, and what we before called "quick," we now call "slaked." What can be stranger than this?" Aurelius Augustine, *The City of God*, Vol. II, ed. Marcus Dodds (Project Gutenberg Ebook, 2014), 419, http://www.gutenberg.org/files/45305/45305-h/45305-h.htm.

75 Kingery et al., "The Beginnings of Pyrotechnology," 220.

76 Calcium carbonate's chemical makeup is CaCO3 (one Calcium, one Carbon, and three Oxygen). By raising its temperature, the heat drives out CO2 and leaves the spirited quicklime, CaO, of St. Augustine's description.

77 When water is added to quicklime, Ca(OH)2 is created and hydrated, or 'slaked,' lime is produced. St. Augustine's description of the internal fire kindled when others would be extinguished was referencing this process. Once water is added, the stones release heat and turn into a paste. St. Augustine's predecessor, the Greek Theophrastus described this chemical reaction at the turn of the third century BCE when he stated that laborers, "having broken up (the hydrated lime) and poured water on it, they mix it with wooden sticks, for it cannot be mixed with the hand because of the heat." Theophrastus, *On Stones*, ed. Earle Caley and John F.C. Richards (Columbus: Ohio State U, 1956), 59-60.

slaked lime is left to dry, reabsorbing CO_2 and completing the lime cycle.[78] Manipulating materials with fire required the application of heat over a period of time—multiple days and sometimes weeks. Therefore, relatively large amounts of organic fuel were required to produce lime prior to the British breakthrough and well beyond in most places.

The earliest archaeological evidence of lime production include Natufian sites in the Levant that demonstrate the material's use for plaster on flooring and walls as well as for sculptures as early as 12,000 years ago. From this early date, there were two options for lime burning. The Natufian sites included both. The first was open, or covered, pits where fuel and limestone were stacked in a pile and burned. The second, involved trapping heat in an enclosed structure, which the Natufians accomplished in a cave.[79] Comparing these two production methods offers insight into the trade-offs that govern lime production in the organic economy. The Hayonim Cave in modern day Israel was used by, possibly female, Natufians to carry out the lime cycle. The cave served as a sort of kiln that trapped heat in order to calcinate limestone. According to Ofer Bar-Yosef, a leading Natufian archeologist, the cave-kiln was used between roughly 10,400 and 10,000 BCE.[80] This method is an anomaly in Mesolithic archaeology. It does, however, display the trade-offs associated with lime production. By trapping heat, less fuel would have been required to produce lime. It was likely due to needing less biofuel that the cave remained in use for so long. Persisting in a central location would have had its costs. The

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78 In the third phase of the lime cycle, slaked lime is exposed to the atmosphere where CO2 is reintroduced as H2O is driven off through evaporation. The chemical makeup of the material returns to CaCO3 as the lime cycle is completed.

79 Kingery et al., "The Beginnings," 223.

80 Ofer Bar-Yosef, "The Natufian in the Southern Levant," in *The Hilly Flanks and Beyond*, eds. Cuyler Young, Jr., Philip Smith, and Peder Mortensen (Chicago: University of Chicago Oriental Institute, 1983), 11-42.

more organic fuels were used in the cave-kiln, the further one would have had to go to obtain them. Since the material required being produced in, or near, settled communities, the production could not simply chase the fuel.

This had particular consequences for the second production method. Although the cave-kiln is an informative case study, it was an exceptional ancient production site. The standard form of producing lime in the ancient world included burning lime in open air or earth-covered pits loaded with lime and fuel. This was a much preferred alternative to the cave-kiln as demonstrated by the abundance of archeological sites.[81] As with the cave, this method also had trade-offs. Little is known about the precise materials and practices that our ancient ancestors used to produce lime and their environmental costs. However, conclusions can be drawn from more contemporary examples. In a recreation of traditional Mayan lime burning sites, tests carried out by architectural historians Thomas Schreiner and Jean-Pierre Protzen determined that open air burning required large amounts of biofuel.[82] With no method for trapping heat, the average ratio of fuel to quicklime produced was 5:1.[83] This more recent example has all of the pitfalls of historical upstreaming, but it clearly demonstrates the disadvantage of the open air method. Much more fuel was necessary to carry out the lime cycle. When compared to the ratio of the kiln at 2:1, the amount of fuel more than doubles. These are not precise

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81 Michael B Toffolo, Micka Ullman, Valentina Caracuta, Steve Weiner, and Elisabetta Boaretto, "A 10,400-year-old Sunken Lime Kiln from the Early Pre-Pottery Neolithic B at the Nesher-Ramla Quarry (el-Khirbe), Israel," *Journal of Archaeological Science: Reports* 14 (2017), 353-64.

82 In the study, the superior heat produced by fresh cut timber was noted as "the basic requirement of traditional Mesoamerican lime burning technology is freshly harvested organic fuel with average moisture content close to 50%." Thomas Schreiner and Jean-Pierre Protzen, "Traditional Maya Lime Production: Environmental and Cultural Implications of a Native American Technology" (PhD Diss., University of California, Berkeley, 2002), 28.

83 Schreiner and Protzen, "Traditional," 34.

methods for determining the amount of fuel needed to produce lime. However, they do demonstrate the advantage of the kiln. It required less fuel.

An extensive lime production complex persisted in the eastern Mediterranean World from the Natufians' first use of lime to the 6th millennium BCE. Regardless of the method of production, maintaining such a system required consistent inputs of fuel. Thus, lime industries may very well have been the first to demonstrate the energy limits of settled societies. It can be assumed that the longevity of the first wave of intensive lime production in the Mediterranean World (from roughly 12,000 y.a. to 8,000 y.a.) was likely due to the environmental advantages of the region. The limestone mountains in the Levant, covered with timber, provided the ideal landscape for lime production. Since manufacturing lime in the organic economy requires large amounts of firewood, there are significant sacrifice zones associated with such production. An ancient example of the depletion of organic fuels by thermal industries which produce lime includes a site in the southern Levant known as "Ain Ghazal." By the 7th century BCE, the settlement had "systematically deforested the immediate vicinity of the settlement, creating a de-vegetated area with a radius of 3.0 km or more from the center of the settlement."[84] This was largely due to the need to feed thermal industries. Kingery et al. estimated that the ratio of biomass to quicklime for ancient lime production was around 2:1.[85] Artioli et al. deduced that it would take "4 to 8 tons of wood…to produce quicklime necessary…[to

84 Gary O. Rollefson and Ilse Köhler-Rollefson. "Early Neolithic Exploitation Patterns in the Levant: Cultural Impact on the Environment." *Population and environment* 13, no. 4 (1992), 243–254.

85 These estimates are based off an 1865 tract by Burnell. "Measurements have shown that for each tone of quicklime produced in 19th-century kilns about 1.8 tons of limestone rock and two tons of wood (fir) fuel were required (Burnell 1865). For open-pit firing about twice that amount of fuel, or more, would have been needed." Kingery et al., "The Beginnings of Pyrotechnology, Part II," 221.

plaster] one house."[86] There are many variables that would determine the amount of fuel used in lime production and the estimates are far from precise. Nevertheless, they demonstrate the connection between lime production and organic fuels. Although lime based materials seem inorganic, prior to the British method, it likely required as much or more timber to build with these materials than organic alternatives.[87] Claiming that the collapse of the lime industry in the Levant was the result of outstripping fuel alone would be a reductionist proposition with little evidence to support it. However, the trade-offs associated with producing lime in the organic economy were clearly present.

For reasons unknown, archaeological evidence of lime production sites diminish for roughly four thousand years and re-emerge with the Iron Age societies in the Mediterranean World. This introduced a new context to the use of the material that was now added to the material regimes identified by Wertime and made to serve the demand from highly stratified societies. The ancient Minoans demonstrated this as they revived lime production for use in elaborate plaster works for elite dwellings.[88] This use of lime plasters was maintained in Crete, Cyprus and other regions until the Minoan collapse around the late 2nd millennium BCE. A second noteworthy adaptation of the Minoans involved using crushed tiles or bricks to waterproof the plasters for use in cisterns and other hydraulic infrastructure.[89] The baked clay provided a method to achieve a sort of

86 Artioli et al., "The Vitruvian Legacy," 162.

87 There exists robust debate over whether or not lime production leads to the collapse of organic fuels. I will not weigh in one way or the other, but these can be seen in the Yucatan and Mayan production sites, see: Clark "A Burning Question," 201 and Seligson et al., "Burnt Lime."

88 Artioli et al., "The Vitruvian Legacy," 162.

89 Artioli et al. describe cisterns, bathtubs and aqueducts use of this material throughout the Greek world as well. Artioli et al., "The Vitruvian Legacy," 166.

pozzolanic material, although on a limited scale that also required firing of its additives. These lime uses persisted in Minoan society until its mysterious collapse. A leading hypothesis for their downfall was related to volcanic activity.[90] One of the largest volcanic eruptions in recorded history rocked the Minoan world around 1500 BCE.[91] The Minoan eruption, as it is known today, involved a volcanic explosion near the island of Santorini (Thera), to the west of Crete. Although occurring roughly a century beforehand, this likely hastened the decline of the Minoans who were conquered by the Mycenaeans around roughly 1400 BCE.[92]

The volcano's caldera formed a ring to the west of Crete in the Mediterranean. Following the eruption, the Santorinis—those who settled in this volcanic ring—discovered a unique advantage in the pyroclastic flows beneath their feet.[93] They mixed the volcanic sand with lime to create a durable plaster for building and one with waterproof qualities. This was possibly the first use of volcanic sands to such an end. There are two possible explanations for why the Santorini's used volcanic sand in this way. The first is that they inherited the knowledge of the properties of silica rich additives from the Minoans and simply found a substitute for crushed bricks and tiles. The second is related to the environmental possibilities of the region. In the introductory

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90 Nixon, I.G. "The Volcanic Eruption of Thera and Its Effect on the Mycenaean and Minoan Civilizations," *Journal of archaeological science* 12, no. 1 (1985): 9–24.

91 Nixon, "The Volcanic," 9.

92 T. H. Druitt, L. Edwards, R.M. Mellors, D.M. Pyle, R.S.J. Sparks, M. Lanphere, M. Davis, and B, Barreirio *Santorini Volcano*, *Geological Society Memoir (Geological Society of London)*; No. 19 (London: Geological Society, 1999), 49.

93 J. P. Oleson and M. D. Jackson, "Chapter 1: The Technology of Roman Maritime Concrete," in Brandon et al., *Building for Eternity*, 3.

chapter to *Lea's Chemistry of Portland Cement*, industrial historian Robert G. Blezard wrote that, "the mortar used by the peasants of Santorin – an island destitute of wood for building – long remained identical in its composition and preparation with that of ancient times."[94] Regardless of the construction methods being an ancient inheritance or a method born of necessity, the sands of Santorini remain a possible origin for pozzolan cements. For instance, Blezard proposed that, "the Greeks employed for this purpose the volcanic tuff from the island of Thera (now called Santorin) and this material, known as Santorin earth, still enjoys a high reputation on the Mediterranean."[95]

The Romans created a similar concoction, but with pozzolan sand. They were awed by the material's unique properties. The Roman naturalist Pliny the Elder described the phenomenon of pozzolan cement setting under water when he wrote, "as soon as it comes into contact with the waves of the sea and is submerged, [pozzolan cement] becomes a single stone mass, impregnable to the waves and every day stronger."[96] These properties were related to the silica, or silicon dioxide, content of pozzolan sand.[97] It is found in a condensed state in volcanic sands, due to the compression caused by volcanic eruptions.[98] Today, scientists refer to the process of creating a new compound by mixing

94 Blezard, "History of Calcareous Cements," in *Lea's Chemistry,* 3.

95 Blezard, "History of Calcareous Cements," 3.

96 Pliny the Elder, *The Natural History*, trans. John Bostock and Henry T. Riley (London: Taylor and Francis, 1855), Book XXXVI, Ch. 53, accessed June 4, 2021 http://www.perseus.tufts.edu/hopper/text?doc=Plin.+Nat.+toc.

97 Franco Massazza, "Pozzolana and Pozzolanic Cements," *Lea's Chemistry of Cement and Concrete.* 4th ed. Editor Peter Hewlitt, Originally edited by F.M. Lea (Elsevier Science & Technology, 2003), 471-472.

98 Massazza, "Pozzolana," 471-472.

slaked lime with silica rich sand as a pozzolanic reaction.[99] This allowed cements to set under water. By adding such sands, the Romans also created a compound of calcium-aluminum-silicates-hydrates (C-A-S-H). This strengthened Roman cement by compressing the spaces between molecules. As the Roman architect Vitruvius observed, "this substance when mixed with lime and rubble not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water."[100]

Roman pozzolan cement was likely invented around the present day city of Naples, located in a large volcanic caldera known as the Phlegraean Fields. The first large-scale use of Roman maritime concrete was at the Roman port at Cosa, likely built in the 2nd century BCE.[101] Debates over the connection between the two instances of using volcanic sands to produce durable and waterproof cement persists. Blezard and others see the pozzolan cement transition as growing from the Greek applications with sand from Santorini. Recently, the Roman Maritime Concrete Survey (ROMACONS), based on sampling of various ancient structures, found no use of pozzolan cements in Greek sites, thereby contradicting the history provided by Blezard.[102] This mystery may never be solved. Regardless of the origins of the use of volcanic sand mixed with lime, the use of

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99 Science Direct, "Pozzolanic Reaction," https://www.sciencedirect.com/topics/engineering/pozzolanic-reaction.

100 Vitruvius, *Ten Books,* 67.

101 McCann, Anna Marguerite, "The Harbor and Fishery Remains at Cosa, Italy," *Journal of field archaeology* 6, no. 4 (1979): 391–411.

102 J. P. Oleson and M.D. Jackson, "The Technology of Roman Maritime Concrete," in *Building for Eternity: The History and Technology of Roman Concrete Engineering in the Sea,* eds. C. J. Brandon, R. L. Hohlfelder, M.D. Jackson, and J.P. Olsen (Havertown: Oxbow Books, 2014), 3.

pozzolanic materials never reached a scale to be considered a cement transition until the Roman adaptations.[103]

A central claim of this dissertation is that cement transitions require much more than raw material and fuel availability. Material availability as well as techniques, organization and demand for large-scale building converged at the imperial moment. One example of these convergent forces involved the construction of the port at Caesera between 22 BCE and 10 BCE. This Roman port constructed in the early imperial period, is located on the coast of the Levant and required 52,000 tons of pozzolans to create its artificial sea breaks.[104] The economics of transporting such sands from Italy could be explained with the material's use as ballast weights in route to Alexandria for grain shipments as part of the imperial trade networks.[105] Using pozzolan for ballast weights seemed common as at least one ancient Roman shipwreck included a vessel loaded with sand below decks for stabilizing as well as delivery purposes.[106] Timber abundance was also necessary for the forms that shaped what became the largest man-made protected port in the Mediterranean. Archaeologist Piero Gianfrotta estimated that "some 8 to 9 species, from the central and northern Mediterranean and it is estimated that some 6,000 tons of wood were transported overall."[107] Following this use at Caesarea, pozzolan

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103 Oleson and Jackson, "The Technology," 3.

104 Piero A. Gianfrotta, "Comments Concerning Recent Fieldwork on Roman Maritime Concrete." *The International journal of nautical archaeology* 40, no. 1 (2011), 190.

105 Oleson and Jackson, 7.

106 R. L. Hohlfelder and J. P. Olsen, "Roman Maritime Concrete Technology in its Mediterranean Context," in *Building for Eternity: The History and Technology of Roman Concrete Engineering in the Sea,* eds. C. J. Brandon, R. L. Hohlfelder, M.D. Jackson, and J.P. Olsen (Havertown: Oxbow Books, 2014), 40.

107 Piero A. Gianfrotta, "Comments Concerning Recent Fieldwork on Roman Maritime Concrete." *The International journal of nautical archaeology* 40, no. 1 (2011), 190.

cement was used extensively throughout the ancient Mediterranean World in ports, harbors, and fish ponds for centuries. By the fall of the Western Roman Empire, structures made from Italian pozzolan deposits were abundant. The ROMACONS project found sites outside of the Italian peninsula in present day Tunisia, Libya, Algeria, Egypt, Greece, Turkey, but, interestingly, identified a lack of sites in the western Mediterranean World, with the exception of "only one on southern coast of Portugal, at Quarteira…probably a fish-pond."[108]

Around 23 BCE, the Roman poet Quintus Horatius Flaccus (a.k.a. Horace) described the use of pozzolan cement in such fish ponds. "The fish feel their waters shrinking as pier after pier is pushed into the sea. The contractor with his workmen repeatedly tips in rubble; at his side is the owner who is bored with living on land."[109] Horace wrote at the start of the Roman Empire, but the demand for building by wealthy Romans was clearly described. Had the material developments of the previous centuries not been available, the ability to dump pier after pier in the Mediterranean would have been severely limited. When considered in a global historical context, it becomes clear that this was an invention born of a unique geographic endowment and the scale of building afforded by and demanded of maritime empire. The ancient Roman Empire was the only instance where these factors led to a cement transition. The Mediterranean volcanic zone afforded an advantage over the waterproof compounds produced with

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108 For detailed explanations, photographs, maps and drawings of these sites, see: C. J. Brandon and R. L. Hohlfelder, "History and Procedures of the ROMACONS Project," in Brandon, Hohlfelder, Jackson, Oleson, Bottalico, Hohlfelder, Robert L., Jackson, M. D., Oleson, John Peter, Bottalico, L., *Building for Eternity the History and Technology of Roman Concrete Engineering in the Sea*. (Oxford: Oxbow Books, 2014), 121-140.

109 Q. Horatius Flaccus, *Odes and Epodes,* trans. Niall Rudd (Harvard: Harvard University Press, 2004), 143.

crushed tiles or ceramics, a method used by both the Minoans and Greeks.[110] These materials required firing before being crushed to mix with lime. Pozzolan sands, on the other hand, proved much more plentiful and therefore could be used on a much greater scale. It also avoided organic inputs, like the sticky rice mortars used in China centuries later. The same volcanic catastrophes that ended the Minoan civilization and later froze Pompeii in time, gifted the Romans abundant pozzolan sands that they then turned into durable and waterproof cement. The dynamics of this cement transition are most visible in the City of Rome.

City of Cement

By the time Augustus set out to build a Roman empire and rebuild its metropole, there was a wide variety of materials available to builders in the city. They each had limitations. Metals were poor structural materials due to their susceptibility to rust. Timber was susceptible to fire. Brick had to be bonded in order to serve urban building purposes. This made cement made of lime the primary material for the large-scale construction in the city. Pozzolan cement was used extensively in the metropolis throughout the imperial period to transform it from a settlement that regularly burned and flooded to a relatively secure imperial capital. Augustus set about to construct monumental buildings after assuming the role of emperor in 27 BCE. Many different marble structures and grand squares were constructed under his tenure. Following this example, the monuments of the Pantheon and Colosseum rose after his death. The city's homes began a transformation from mud, straw and wood buildings to fired brick, mortar and concrete at this time as well. Augustus seemed to have supported the use of fired

110 Artioli et al., "The Vitruvian Legacy," 166.

brick and a maximum wall thickness of around a foot and a half.[111] After Nero's fire of 64 AD, the building codes required construction of such building for their fire-resistant qualities.[112] Augustus also assigned cronies, most notably Agrippa, to the tasks of building sewage networks and preventing flooding along the Tiber River.[113] This process continued through the imperial period as well. Much of this building was carried out with armies of enslaved people using pozzolan cement. Without such abundance of materials, it is questionable whether or not the urban population of the City of Rome could have reached the population size of over one million inhabitants, which was unique in the ancient world.[114]

Although slavery, conquest and overexploitation of resources would all prove the downfall of this city of cement, the course set by Augustus sustained its population growth.[115] It is important to note that pozzolan cement building did not occur in a vacuum nor was it the result of resource scarcity. It demonstrated a fundamental feature of cement societies and their associated building regimes; namely, material abundance is crucial for sustaining them. As mentioned above, the Mediterranean World at the turn of the Common Era was an area of building material plenty. Pozzolan cement was simply an addition to a much larger material portfolio in the ancient capital. It is not known when pozzolan cement was applied to building, but Cato the Elder described use of the material

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111 Favro, "'Pater Urbis,'" 74.

112 Favro, "'Pater Urbis,'" 73.

113 Favro, "'Pater Urbis,'" 74.

114 Diane Favro, "Reading Augustan Rome: Materiality as Rhetoric In Situ." *Advances in the history of rhetoric* 20, no. 2 (2017): 188.

115 Well known concrete structures include the Pantheon and Colosseum.

in walls and foundations around 160 BCE.[116] Sometime following 121 BCE, concrete gained widespread use, evolving into the method of floating crushed bricks and stones in large amounts of mortar by the Imperial Age.[117] This was only one piece of a much larger Mediterranean building material complex. Augustus' arrival in the City of Rome came at a time when ancient thermal production had reached maturity.

Lime production still had unique requirements. As mentioned above, metals could be imported and production could be carried out near organic fuel rich environments away from the city. This shortened the distance between raw materials and fuel, but often lengthened the distance between the site of production and consumption as fuel supplies were exhausted and the thermal industries were relocated.[118] Lime differed in being susceptible to spontaneous combustion, atmospheric ruin and had to remain dry—a challenging task for pre-industrial transportation. This dictated that the production site for cement's essential ingredient was best located near the site of consumption. From its earliest use as plasters for lodgings, its production was carried out in or near settled areas.[119] In order for cement production to be sustained, materials had to be brought to the production site near or in the city. This made transportation another significant feature of lime's production triangle. The movement of bulk goods can be imagined as the lines that connect the dots of fuel, raw materials and the site of production/consumption. Prior

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116 Cato the Elder, "*De Agri Cultura*," Ch. 38.

117 K. D. White, *Greek and Roman Technology* (Ithaca, N.Y.: Cornell University Press, 1984), 85.

118 "Following the fuel," so to speak, persisted well into the modern Industrial Age with iron industries of Europe. Braudel noted of early modern iron industries that, "as soon as the radius from which a wood-burning factory drew its supplies became too large and costs increased, the response was if anything to move the factory." Fernand Braudel, *Civilization and Capitalism 15th-18th Century*, Vol. 1, trans. Sian Reynolds (London: William Colins Sons & Co., 1985), 366.

119 Kingery et al., "The Beginnings of Pyrotechnology, Part II," 219.

to the railroad, materials and fuels could either be transported on land or water, the latter being much more economical. For this reason, the ancient city held an advantage due to the access to water transportation along the Tiber River.

Water transportation in the imperial metropole allowed for the import of materials from throughout the Mediterranean. This feature was essential for cement production and concrete building. Wertime went so far as to describe the "concrete city of Rome with its rivers of running water, emergent windows of glass, terra cotta roofs, and lavish use of bricks…indeed, was a quarry of pyrotechnologic materials."[120] There were a few further geographic attributes that made this all possible. First, lime did not require as much energy as other thermal industries. The production of metals, although outside of the city's construction material matrix, provides an example of the environmental costs of different thermal industries. Metallic ores needed to be in direct contact with charcoal.[121] Charcoal production required large amounts of wood and was often produced through open air burning. Energy historian Vaclav Smil provided an overview of the trade-off for this ancient fuel type. "In mass terms up to 15 units of wood were need[ed] for a unit of charcoal, and even with a lower, typical preindustrial mean of 5:1 this conversion entailed about 60% loss of initially charged."[122] Charcoal and iron production was often carried out away from populated areas where firewood was plentiful. Based off of estimates of charcoal use in Italian iron production around the first century BCE provided

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120 Wertime, "The Furnace Versus the Goat," 447.

121 Ronald F. Tylecote, "Furnaces, Crucibles, and Slags," in *Coming of the Age of Iron,* ed. Theodore Wertime (Yale: Yale University Press, 1980), 183.

122 Vaclav Smil, *Energy Transitions History, Requirements, Prospects* (Santa Barbara, Calif.: Praeger, 2010), 27.

by Wertime, this produced a fuel to finished product ratio of 15:4.[123] Therefore, iron production was much more energy intensive than the production of building materials. Cato the Elder instructed the reader that, "if you cannot sell your firewood and faggots, and have no stone to burn for lime, make charcoal of the firewood, and burn in the field the faggots and brush you do not need."[124] His advice indicates the production of lime did not require charcoal, but ancient lime kilns were still fuel hungry. For example, Wertime observed the fuel requirements "in traditional Greece a single lime kiln required 1,000 muleloads of juniper wood for one burn, 50 kilns requiring 6,000 metric tons of wood yearly."[125]

Kilns did save wood as they trapped heat in the firing process, reducing the necessary amount of fuel. Cato the Elder also provided insight into the Roman kiln. He instructed his fellow property holders to build a "lime-kiln ten feet across, twenty feet from top to bottom, sloping the sides in to a width of three feet at the top…Be careful in the construction of the kiln; see that the grate covers the entire bottom of the kiln."[126] Archaeologist Brian Dix demonstrated that, by the imperial period, the Roman lime kilns were more "squat and square," but had similar interior dimensions.[127] They also remained periodic or 'flare' kilns, where the entire charge would be removed with each burn. Dix further estimated that it would take a total of 12 days to produce enough lime for one

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123 Wertime, "The Furnace Versus the Goat," 452.

124 Cato, *De Agri Cultura,* Ch. 38.

125 Wertime, "The Furnace Versus the Goat," 452.

126 Cato the Elder, *De Agri Cultura*, Ch. 38.

127 Brian Dix, "The Manufacture of Lime and its Uses in the Western Roman Provinces," *Oxford Journal of Archaeology* 1, no. 3 (1983), 332.

large house.[128] That would include roughly 5m^3 of lime and "the equivalent of an oak trunk .5 m in diameter or 10 m. long or two fir trunks of the same size."[129] Dix estimated that this amount of lime would have made roughly 20m^3 of mortar (mixing mortar to sand at 1:3 as suggested by Vitruvius), which would have been enough to bond roughly 200 m^3 of masonry bricks.[130] Bricks required abundant amounts of organic fuel to produce as well. In the city, historian Michael Williams estimated that "every cubic meter (1.0m^3) of burnt brick required nearly 150m^3 of wood to make. Bricks also had to be fixed to one another, and intense heat was required (900 Celcius-1100 Celsius, depending on the type of stone used) to calcinate or reduce calcium carbonate (limestone or chalk) to lime, the basis of cement, plaster, and ultimately concrete. Each ton of lime required between 5 and 10 tonnes of wood to produce, depending on the quality of the wood."[131] When added to the use of wood for frames and scaffolding, it is debatable whether or not building (and rebuilding) the city with timber would have had more or less cost on the available biomass within reach of the city.

Therefore, resource abundance was a central feature of the Roman cement transition and associated concrete building revolution. Around the time Augustus entered the city, Rome had abundant supplies of timber resources and organic energy. In the first

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128 The process included two days to load, 3-4 days to calcinate, 4 days to cool and 2 days to unload. Dix, "The Manufacture," 336. For a description of a Roman lime kiln, see: D.A. Jackson, L Biek and Brian Dix, "A Roman Lime Kiln at Weekley, Northants," *Britannia (Society for the Promotion of Roman Studies)* 4 (1973): 128–140.

129 Dix, "The Manufacture," 337.

130 Jackson et al., "A Roman Lime Kiln," 130.

131 Michael Williams, *Deforesting the Earth from Prehistory to Global Crisis: an Abridgment* (Chicago: University of Chicago Press, 2006), 75-76.

century CE, the Greek Dionysius of Halicarnassus observed of such abundance on the peninsula. He wrote,

> Italy does not, while possessing a great deal of good arable land, lack trees, as does a grain-bearing country; nor, on the other hand, while suitable for growing all manner of trees, does it, when sown to grain, produce scanty crops, as does a timbered country; nor yet, while yielding both grain and trees in abundance, is it unsuitable for the grazing of cattle; nor can anyone say that, while it bears rich produce of crops and timber and herds, it is nevertheless disagreeable for men to live in…But most wonderful of all are the forests growing upon the rocky heights, in the glens and on the uncultivated hills, from which the inhabitants are abundantly supplied with fine timber suitable for the building of ships as well as for all other purposes. Nor are any of these materials hard to come at or at a distance from human need, but they are easy to handle and readily available, owing to the multitude of rivers that flow through the whole peninsula and make the transportation and exchange of everything the land produces inexpensive.[132]

The quote is worth reproducing in its entirety. It demonstrates the timber abundance at the dawn of the first cement transition. Timber for building and fuel use came from the Alban Hills, floated in on the Tiber River, while larger timbers were harvested in the Apennine Mountain Range, floated down rivers to the sea and then floated up the Tiber to the city.[133]

Through these networks, Rome also had access to abundant pozzolans and calcium carbonate, relatively easily shipped to the capital city by the Tiber River. Archaeologist Mary Jackson observed that the "Pozzolane Rosse erupted at 456 ± 3 ka from nearby Alban Hills volcano filling valleys and covering topographic plateaus across the Roman region." This material was "used this mortar formulation in the principal

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132 Dionysius of Halicarnassus, *Roman Antiquities*, trans. Earnest Cary (Loeb Classical Library: Harvard University Press, 1837-1950), Book I, Ch. 37, accessed June 4, 2021, http://penelope.uchicago.edu/Thayer/e/roman/texts/dionysius_of_halicarnassus/home.html.

133 Williams, *Deforesting the* Earth, 76.

Imperial monuments constructed in Rome through early fourth century CE."[134] This material improved the quality of cement and afforded durable construction. Fire may have been the reason to promote building with such mortars in the City of Rome, but this was only possible due to the large pozzolan deposits around the city. Another geologic endowment was provided to the city by the Apennine Mountain Range. Geologist Grant Heiken writes of its composition, "this range is made up of mostly sedimentary rocks that were deposited in ancient seas, subjected to elevated temperatures and pressures while deeply buried, consolidated, then thrust up to their present elevation, where they form "'the backbone of Italy.'"[135]

Despite such resource abundance, the Roman industries still existed in the organic economy where any increase in production also had associated trade-offs with land use. This was problematic for a building regime that included many thermal industries like glass, bricks and terra cottas, let alone cement. Although building with such materials persisted in and around the city for roughly four centuries, the Romans seem to have reached a production ceiling around the same time that the empire collapsed. Wertime wrote of the wood fuel catastrophe of the ancient world as, "Western civilization was overtaken by problems of environment and energy rivaled only in Han Dynasty China and thereafter."[136] Historian J. Donald Hughes argued that in the ancient Mediterranean,

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134 Marie D, Jackson, Eric N Landis, Philip F Brune, Massimo Vitti, Heng Chen, Qinfei Li, Martin Kunz, Hans-Rudolf Wenk, Paulo J M Monteiro, and Anthony R Ingraffea, "Mechanical Resilience and Cementitious Processes in Imperial Roman Architectural Mortar," *Proceedings of the National Academy of Sciences - PNAS* 111, no. 52 (2014), 18484–18485.

135 Grant Heiken, Renato Funiciello, and Donatella de Rita, *The Seven Hills of Rome: a Geological Tour of the Eternal City* (Princeton: Princeton University Press, 2005), 137.

136 Wertime, *Coming of the Age,* 9-10.

for example, fuel consumption accounted "for perhaps 90 percent" of wood use.[137] Although the Roman lime kilns achieved a far greater fuel efficiency than metallic ones, the use of fuel remained immense. Historian Michael Williams estimates that "By the fourth century AD, 3,000 wagonloads of lime were required in Rome annually, half for aqueduct maintenance and the development of glass manufacturing (and glass blowing) is added to that of bricks and tiles, then the energy requirement in building alone must have consumed a vast amount of wood."[138] The scale of thermal production in the organic economy as impressive, but not without limits.

Another point that deserves mentioning involved the growth of agriculture in the imperial age due to the macabre incentives of the *latifundia* slave agricultural system. Land dedicated to agriculture reduced the area that could be used for building timber or firewood. In a lament by Pliny the Elder, writing two centuries after Dionysus, the Roman naturalist observed that "latifunidia perdidere Italiam: the latifundia have destroyed Italy."[139] The *latifundia* slave agricultural system rotted Roman society and destroyed the environment. The shocking statistic that as much as 35% of the Roman population were slaves gives an idea of the scale of the plantation system, one that incentivized overexploiting agricultural resources for profit.[140] Radkau observed that by 200 CE the problem of abandoned fields, likely due to soil depletion was readily

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137 J. Donald Hughes, *The Mediterranean: an Environmental History* Santa Barbara (Calif: ABC-CLIO, 2005).

138 Williams, *Deforesting the Earth,* 75-76.

139 Pliny the Elder, *The Natural History*, Ch. 7.

140 Walter Scheidal, "Human Mobility in Roman Italy, II: The Slave Population," *The Journal of Roman Studies* 95 (2005), 65.

apparent.[141] This also led to the depletion of wood sources in the hills around the Mediterranean.[142] Construction timber, firewood and agricultural goods all required land and increases in one always had associated costs with the other in the organic economy.

There is no one clear cause for the decline of the Roman building regime. Investment for building projects seemed to decline around the fourth century CE due to the cost of fighting on the frontiers.[143] Certainly war spending at the neglect of building and infrastructure is a well-known trend of empire. However, one must question the impact that the Roman Empire had on the resources of the Mediterranean Basin. The City of Rome was the center of concrete building, but also demonstrated the cost of the sustained use of anthropogenic stones in a central location. Although water transportation and kiln technology allowed for monumental building, fire-resistant building and hydraulic construction, the urban metabolism of a large city put pressures on the surrounding environment for timber, firewood and agriculture. In the organic economy, each competed for the same land. Whether or not the limits of the organic economy ended the first concrete revolution is unknown. However, it seems apparent that maintaining the concrete capital of Rome in the organic economy would have been difficult, if not impossible. Nevertheless, the monumental building in the city demonstrated the possibilities of cement's use to future empires. Although the materials and demand for an extensive cement building regime ceased, the techniques and

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141 Joachim Radkau, *Nature and Power: A Global History of the Environment*, 1st English ed. (Washington D.C.: German Historical Institute, 2008), 154.

142 K.D. White states, "Faventinus (fourth century) and Palladius (perhaps a half century later) belong to a period when the great age of imperial concrete structures was already at an end." White, *Greek and Roman* Technology, 85.

143 Heather, *The Fall of the Roman Empire*, 440.

organizational knowledge for creating such a cement society persisted across the floodplain of the Western Roman Empire.

Western European Building Regime

Venerable Saint Bede looked back on the Roman monuments in the eight century and expressed that "as long as the Coliseum stands, Rome shall stand; when the Colosseum falls, Rome will fall; when Rome falls, the whole world will fall."[144] Due to a lack of maintenance and deterioration of materials, the structure—made of Roman bricks, cement and concrete—did partially collapse in the Middle Ages. The crumbling monument of ancient Rome was, and still is, symbolic of the ancient Roman building regime. Once the necessary conditions for sustaining a concrete building regime were no longer met, the scale of cement production decreased dramatically in Rome and across the empire. Renaissance builders looked back to the coliseum and explored the Roman socio-technical inheritance in order to improve building with anthropic stones in their own time. They then influenced the builders of the early modern age.

Although cement was adapted to specific ends and shaped by regional materials availability, its production with biofuel in kilns was a nearly universal pan-European method for producing anthropogenic stones well after the decline of the Roman building regime. The Mediterranean World may have experienced significant deforestation by the third century CE, but western Europe remained a zone of organic energy abundance. Williams noted the natural bounty across Western Europe in the Late Middle Ages, "the abundance and ubiquity of wood in medieval Europe was matched by an extraordinary endowment of other natural resources, especially constantly flowing streams and diverse

144 Quote reproduced in Edward Gibbon, *The Decline and Fall of the Roman Empire* Vol. III (London: Frederick Warne and Co., 1781), 810.

and abundant minerals."[145] European environmental history during the Middle Ages is a story of a war on wood as clearing forests for building towns and agriculture was the aim of the ecological conquest of western Europe.[146] Such timber abundance also provided resource wealth. The timber of the continent remained an advantage as Braudel wrote of the early modern period that "one of the reasons for Europe's power lay in its being so plentifully endowed with forests."[147] This included timber's use in ship building, as mine structures, for tools and building as well as many other purposes. From the fall of the Roman Empire through the early modern period, western Europe remained largely a timber abundant region.

The material was so ubiquitous that historian of technology Lewis Mumford described the period between 1000 and 1800 as an "Eotechnic"—a technological epoch where wood was the primary structural material.[148] He wrote, "first of all, wood was the foundation of all its [Europe's] buildings. All the elaborate masonry forms were dependent upon the work of the carpenter…the fact is that none of this construction was possible without an elaborate falsework of wood: nor without wooden cranes and windlasses could the stones have been conveniently raised the necessary heights."[149] One could also add bond timbers, necessary to hold brick and mortar building together to this architectural list. As was true with the ancient Romans, stone and brick building may

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145 Williams, *Deforesting the Earth*, 92.

146 Robert Bartlett, *The Making of Europe: Conquest, Colonization and Cultural Change, 950-1350* 1st ed. (London: Allen Lane, 1993), 133-166.

147 Braudel, *Civilization and Capitalism*, 362.

148 Lewis Mumford, *Technics and Civilization* (Chicago: The University of Chicago Press, 2010), 119.

149 Mumford, *Technics and Civilizations*, 119.

have seemed like timber substitutes, but were firmly in the organic economy because they required wood to complete. This was also due to the production of plasters and mortars with firewood. Braudel wrote of the centrality of organic energy to European societies as "civilizations before the eighteenth century were civilizations of wood and charcoal, as those of the nineteenth century were civilizations of coal."[150] Like the Romans, the thermal industries of the late Middle Ages and Early Modern periods were fed with organic fuel throughout western Europe. When coupled with the masonry forms, scaffolding and bond timbers, brick and mortar building was far from a substitute for organic building materials on the continent. In fact, it is possible that it took more wood to build with brick and mortar than timber alone in the organic economy.

The building regimes of western Europe were also related to the dominant socio-political context of the time. Following the collapse of the Western Roman Empire, European construction reverted to timber and quarried stone. Brick and mortar building was slowly revived and was extensively used in the pan-European architectural movement known as the Gothic. Historian Eric Jones noted that, beginning in the 13th century, Gothic brickwork and tile roofs stretched across western Europe "from Prussia to Flanders, Aragon and Old Castile"[151] Although not a substitute for organic building materials, brick and mortar did provide a durable building material with the added advantage of being fire resistant. For centuries, building did not occur on a grand scale due to a lack of political, organizational and economic structures that demanded it.

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150 Braudel*,* *Civilization and Capitalism*, 362.

151 E. L. Jones, *The European Miracle: Environments, Economies, and Geopolitics in the History of Europe and Asia*. 3rd ed. (Cambridge, UK; New York, NY: Cambridge University Press, 2003), 40-41.

Materials historian John Harvey also observed that this building materials revival and its maintenance through the early modern period relied on lime as, "with the single exception of plaster of Paris, there was no other available matrix for mortar."[152] The reason to choose lime for use in mortars over plaster of Paris, made from gypsum, is not readily apparent. For instance, the 15th century Italian architect Leon Battista Alberti observed that "stone for gypsum needs to be roasted for no more than twenty hours, whereas that for lime needs at least sixty."[153] In the organic economy, plaster of Paris made from gypsum would have proved a more efficient material. Alberti explained the downside of the material, "gypsum must be used only in an extremely dry place."[154] Calcium carbonate provided advantages due to being water resistant, but its choice over gypsum also demonstrated energy abundance in European thermal industries. From the late Middle Ages to the Industrial Age, most European locations could produce the more energy intensive material.

Brick and mortar made with lime, were thus often preferred in building. Alberti spoke glowingly of the material when he wrote that, "from what I have observed from studying very ancient structures, I would be so bold as to state that there is no building material more suitable than brick, however you wish to employ it, though it must be baked rather than raw and firing must be strictly followed."[155] His comment was sensitive to the inputs necessary to creating and maintaining such a materials alternative. The

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152 John Harvey, *Mediaeval Craftsmen* (New York: Drake Publishers Inc., 1975), 113.

153 Alberti, *On the Art*, 54.

154 Alberti, *On the Art,* 176.

155 Alberti, *On the Art*, 50.

practices for producing brick and mortar as well as their relation to European building from the Late Middle Ages forward can be found in many other works of the Renaissance writers of the fifteenth century. Prior to these accounts, these methods for producing building materials and using them were maintained as tacit knowledge passed down through families and trade guilds.[156] These builders with anthropogenic stones expressed themselves in the works they created. It was not until the Renaissance architects of northern Italy sought to manage the process that the written descriptions appear.

One notable written description of manufacturing brick and mortar was provided by the Venetian Vannocccio Biringuccio's whose work on *Pirotechnia* outlined the state of various European thermal industries in the early sixteenth century. He proposed his own theory on the ancient link between the two materials. "When they [the ancients] found them then to be a dry earth, they made a paste of it with water in order to build. And trying to do the same with pure earth [clay], they found, to their astonishment, that instead of burning up it became hard, produced an effect opposite to stones," he wrote.[157] Although he misrepresented the early history of these materials, Biringuccio reflected the perspective of all pre-industrial builders who described bricks as an anthropogenic stone. In that way, they understood brick and mortar to be linked in their production as well as use. As Biringuccio continued, "in order to make stones and soften them, or to return them to their first principles, burn them as do the…alchemists."[158]

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156 Chandra Mukerji, "Tacit Knowledge and Classical Technique in 17th-century France: Hydraulic Cement as a Living Practice among Masons and Military Engineers." *Technology and Culture* 47, no. 4 (2006): 713.

157 Biringuccio, *The Pirotechnia,* 397.

158 Biringuccio, *The Pirotechnia,* 397.

The proliferation of industries dedicated to such tasks is reflected in Biringuccio's description of their ubiquity. He wrote that, "the practice of making bricks is so well known that it seems a shame to write at length of it here."[159] For this reason, he only dedicated one chapter out of many to brick and mortar building. Although relatively brief due the remainder of the work focusing on metals, his work remains the earliest detailed description of the process of creating anthropogenic stones in the western European building regime. It clearly illuminated the connection of such materials to the organic economy. In addition to wood fuels, Biringuccio observed of the process for making bricks, "it [clay] is pressed into the brick moulds made like a box of wood, or into moulds for roof tiles, tiles, flat bricks, square bricks, or whatever other kind is necessary. Bricks are moulded by pressing after placing them on a bench sprinkled with dry sand so that the soft clay may not stick. Then they are put out in yards to dry in the sun. When dry, they are put in a furnace similar to the one that you made for lime, but where that was round this is made square so as to permit filling the furnace better."[160] The wooden molds of brick kilns demonstrated yet another connection of western European masonry to the organic economy. A feature that was only amplified by the need for wood fuel, as Biringuccio advised that bricks are best burned when "a steady fire is applied for eight days."[161]

Mortar made in the western European building regime displayed a similar relation to the organic economy. Biringuccio's depiction of the Renaissance lime kilns differed

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159 Biringuccio, *The Pirotechnia,* 400.

160 Biringuccio, *The Pirotechnia,* 400.

161 Biringuccio, *The Pirotechnia,* 401.

little from that of Cato the Elder. “First, to make lime, make a round pit in a hillside, digging down in an oval shape, so that its hollow is of sufficient capacity to hold the quantity you wish. This is found by measuring with a rule in the same way that one measures both barrels and other hollow things,” he wrote.[162] Once constructed, Biringuccio advised, “now this is filled to the top with those stones that you have or as many as you want.”[163] He continued, “therefore, assuming that this vault has been made resistant, it is necessary to continue the fire with good, dry wood for seven or eight days if possible… depending on the quality of the stones and the season, and also depending on the quality and quantity of the wood.”[164] This was both a labor and material intensive process.

Making lime mortars required greater skill than the brick maker. The knowledge of the lime burner was important for maximizing the efficiency of production and quality of the finished product. This is a significant point as improvements to production in the western European building tradition relied on process over material substitutes or improvements with physical technology. Similar dynamics can be seen with iron production in the organic economy. Historian David Landes observed that, “what they [Iron manufacturers] could and did do was to cut the heat losses, by designing a an effective furnace, by management of the air draught and, above all, by the charging technique—selecting the right proportions of ore and fuel, stacking them in the best way,

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162 Biringuccio, *The Pirotechnia*, 398.

163 Biringuccio, *The Pirotechnia,* 398.

164 Biringuccio, *The Pirotechnia,* 398.

and replenishing the fuel at the later stages without setting up 'cold spots.'"[165] Due largely to the familiarity of the lime burner with the firing method and local materials, their expertise was similarly an essential factor in the efficiency and quality of cement production.

There were, however, basic guidelines that most lime burners followed that stemmed from ancient knowledge. Biringuccio continued, "you must know that, if desired, lime is made from all kinds of stones, although some melt sooner because of their nature. The best, however, are those that are easily burned and, when burnt, completely break up with water…marble and every other stone also serves, but the best is the one that is most alive in its nature, the best purified, and the one that does not melt nor contain any dead earthiness."[166] Alberti echoed the conventional wisdom that "stone containing earth is also considered unacceptable, because of the impurities it leaves in the lime."[167] The advice to use pure limestone comes from Vitruvius and was maintained across the western European building regime well after Biringuccio's and Alberti's observations. He ended that "any quarried stone will make better lime than that gathered from the ground; a shady, damp quarry will contain better stone than a dry one; and lime from white stone, rather than dark, will be easier to plaster."[168] The limiting factor of such requirements involved the site of production and consumption.

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165 David S. Landes, *The Unbound Prometheus: Technical Change and Industrial Development in Western Europe from 1750 to the Present*, 2nd ed (Cambridge, UK; New York: Cambridge University Press, 2003), 32.

166 Biringuccio, *The Pirotechnia,* 399.

167 Alberti, *On the Art,* 54.

168 Biringuccio, *The Pirotechnia,* 399.

Not all lime burners could access quarries of pure calcium carbonate. There were many substitutes across the continent. Alberti described the regional variation of lime production in Europe. “In Gaul, I have seen that architects use lime extracted solely from dark, round, hard stones found in riverbeds,…this lime has certainly shown itself strong and very lasting in both stone and brick buildings.”[169] Furthermore, he noted that “in France, in the coastal region of the Edui, lime is made from the shells of oysters and mussels, for want of any stone.”[170] Likewise, expertise over the manufacture was localized. There were again general rules of thumb. Alberti wrote that, “stone should lose a third of its weight in producing lime to meet with the approval of experts.”[171] The experts stopped there. Otherwise, he acknowledged that “you will learn many things by yourself while working and practicing it, such as how to make a choice of clays, stones, moulds, furnaces, seasons, weather, and the like, and it would take too long if I should wish to tell you all of them.”[172] It was the lime burner who was the true master of the materials they used.

Monitoring the fire was also necessary over an extended period of time. This was a labor intensive process that required the addition of fuel inputs at variables over a period of days. Types of woods, qualities of the raw materials and conditions of the firing technology all impacted the firing process. Firing could have taken too long as well.

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169 Alberti, *On the Art,* 55.

170 Alberti, *On the Art,* 55.

171 Alberti, *On the Art,* 55.

172 Alberti, *On the Art,* 55.

When overfired, the burnt lime lost its ability to serve as a mortar.[173] There were also many dangers associated with this process of burning calcium carbonate. Persistent threats stalked the early modern lime burners. As late as the nineteenth century, engineer George Burnell stressed the possibility of kiln stones, if not properly chosen for the construction of the face of the kiln, "cracking, and bursting with a loud explosion, by the application of heat, [therefore] it is dangerous to use them in the construction of the arches."[174] Additionally, the volatility of quicklime when exposed to water required careful measures to avoid unwanted mixing. Although no written records exist of when these discoveries were made, they must have been hard, even potentially lethal, lessons for the lime burner.

With all of these risks and the usefulness of their knowledge, it comes as a surprise that lime burners were not valued artisans. There was little discussion of the lime burner in these tracts on building. However, a clue to their social position can be gleaned from the Diderot Encyclopédie, which described a "lime kiln worker" as "this name is given to the men who make quicklime." The encyclopedic entry continued, "their job is highly unpleasant because the maintenance of the fire in the kilns demands constant attention, because they work long hours and they are badly paid."[175] In addition to the years of earned knowledge that was required to be an effective lime burner, their job was

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173 This is known as "vitrification" and only in the nineteenth century was this a preferred method for making cement.

174 Burnell, *Rudimentary Treatise,* 32.

175 Denis Diderot, "Lime kiln worker," The Encyclopedia of Diderot & d'Alembert Collaborative Translation Project. Ann Arbor: Michigan Publishing, University of Michigan Library (2007), accessed June 4, 2021, http://hdl.handle.net/2027/spo.did2222.0000.771, Originally published as "Chaufournier," Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers, 3:257 (Paris, 1753).

also dangerous. Although the lime burners took the risks and maintained the know-how, the beneficiaries of lime production were often those who could control the resources that the material was made from.

This brief survey provides an example of the persistence of the Roman cement tradition through the brick and mortar revival in western Europe during the Late Middle Ages. Both of these materials were produced in the organic economy. Brick clamps were also made of wood, brick and lime were fired with organic fuels and frames as well as scaffolding shaped their use in building. Due to all of these connections to the organic economy, it is doubtful that brick and mortar building provided an inorganic alternative to timber. Western Europe was well forested and could support such an industry so reliant on organic inputs to spread lithic building across the continent. This would have been much more difficult and far more inefficient without the skill of the lime burner. In the organic economy, innovation depended on the knowledge of local materials and their tendencies when fired. The most advanced lime burner equaled the most advanced technology. Through the works of Renaissance writers, one gets a glimpse into this world where the lime burner managed local calcium carbonate sources, fuels and firing. The material they created came from an ancient inheritance, but their contemporary adaptations dictated the possibilities of the western European building regime for centuries.

Pozzolanic Revival

The revival of the lime burning tradition in western Europe beginning in the Late Middle Ages and continued throughout the early modern period. Once the western European states consolidated their power and revived seaborne trading, the need for pozzolans increased as well. Belidor's tract on hydraulic building called for the use of pozzolan and pure white limestone in 1753, almost two thousand years after the material's first recorded use at Cosa. Few historians have given due attention to the recovery of ancient Roman methods for producing hydraulic cement at this time. Even meticulous historians like Fernand Braudel ignored the necessary sands for large-scale building in water. His two-volume masterpiece, *The Mediterranean World During the Age of King Phillip,* made no mention of the pozzolans, which continued to serve as the primary ingredient for hydraulic cement since antiquity. This omission is partially related to the timing of the revitalization of the sand trade. It began in the late seventeenth century, well after King Phillip II's death. The first major project that instigated the pozzolanic revival was the Languedoc Canal, built between 1661 and 1681. It has long been recognized by historians that this canal, built by France under the Sun King to connect the Mediterranean and Atlantic coasts of France, was a template for canal building and port technology across Europe. It also provided an example of what could be accomplished with pozzolan cement in the early modern western European building regime.[176]

Although this revival of the use of pozzolan cement in large-scale hydraulic engineering occurred after the death of King Phillip II, the Spanish monarch still had an impact on the geo-political forces that shaped the re-emergence of pozzolan cement. As the son of the Holy Roman Emperor, Charles V, and Isabella of Portugal, King Phillip II inherited many titles—and privileges. Not only the King of Spain, but the lord of the seventeen provinces of the Netherlands and, through his marriage to Queen Mary of

176 L. T. C. Rolt, *From Sea to Sea* (Seyssinet, France: EUROMAPPING, 1973).

England until her death in 1558, the King of England and Ireland. This inheritance was famously squandered. For instance, the Spanish monarch sent a large Spanish Armada to dethrone the Protestant Queen of England, Elizabeth I after Queen Mary's death, in an attempt to re-establish Catholicism there in 1588. His spectacular defeat by the British Navy, assisted by a North Sea storm, weakened the Spanish fleet that was also used against independence movements in the Dutch provinces since 1567. The Dutch resistance was more prolonged, but equally triumphant. Historian John F. Richards succinctly described that the "breakout from Spanish encirclement," started in 1590 and partially completed by 1597, was a defining moment where "the Dutch now controlled the Rhine, Waal, and Ijssel Rivers and reopened them to commercial traffic."[177] Complete independence for the Dutch Republic was not achieved until decades later. The Habsburg King and his predecessors' failures to revive a Holy Roman Empire left the continent an amalgam of fragmented polities.[178]

From this tapestry of different geo-political entities, there emerged two primary supply points of pozzolan sand. Trade in volcanic sands was regulated by mercantilism. This economic ideology also suggested that domestic resources ought to be held dear and exported only for a positive balance of trade. This involved a complicated system of tariffs and trade alliances that often impeded the movement of goods in western Europe. Constant warfare also disrupted the free flow of goods in this tumultuous period of European history. Each of these factors prevented any one early modern European country from gaining unfettered access to all of the materials necessary for sustained

177 Richards, *The Unending*, 41.

178 Paul M. Kennedy, *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000*, 1st ed. (New York, NY: Random House, 1987).

hydraulic cement manufacturing and hydraulic building lagged because of it. Nevertheless, there were inter-European trading zones along the major sea routes that maintained robust trade in materials. One way to consider these "trade zones" is to borrow Braudel's concept of the Mediterranean World. In the case of the Mediterranean World, trade, politics, and culture all developed across boundaries and materials flowed on water transportation networks. A similar "North Sea World" connected the Low Countries and Great Britain.

Each of these trade zones in early modern Europe contained a supply of pozzolanic materials. Pozzolan sands from Italy were still available and the Catholic Church was a main supplier from mines around Rome. Pozzolan sands near the ancient city were taken to the port of Civita Vechia and exported throughout the calm sea. The market increased dramatically with the major construction projects of absolutist France, as symbolized by the Languedoc Canal. The Dutch Republic, on the other hand, developed an alternative. They were uniquely positioned with miles of coastline facing the North Sea and had access to continental trade by existing on the alluvium of multiple major rivers. The Dutch exploited this geographic position to provide their own hydraulic material. Volcanic stones called *tuffstein* were imported from Germanic lands along the Rhine and ground to a powder using the windmill technology adapted originally from draining water in the swampy republic.[179] Once processed, the German basalt created Dutch *trass,* which could then be shipped back up the Rhine river or used in large-scale

179 Richards writes that "the [Dutch] republic contained approximately 1.9 million persons living in an area of about forty-two thousand square kilometers. Probably a fifth of the land area was under water….in the entire early modern period, between 1500 and 1815, the Dutch Republic reclaimed some 250,000 hectares of land." Richards, *The Unending*, 53.

hydraulic construction across the North Sea. The builders of the Westminster Bridge in the 1740s rejected Italian pozzolans in favor of Dutch *trass* in the first recorded instance of both materials being available in Great Britain. Prior to that, British builders relied solely on the ground sands from the Low Countries.

The supply of sand shaped the possibilities of hydraulic building in Europe throughout the early modern period. After the fall of the ancient Roman building regime, the methods for making Roman cement were also retained through tacit knowledge passed down generationally in families and trade guilds.[180] The sites on the Italian peninsula remained supply centers from antiquity forward, but accelerated according to western European building demands for hydraulic structures. In addition to locating records of collapsed mines and deaths among pozzolana miners near Rome dating to the 1500s, historian Roberto Gargiani uncovered an informative report, written in 1802, from the Commissioner of Roman Antiquities, Carlo Fea that speaks to this ancient tradition. It noted that, from May 17, 1580, a decree was in place regarding the safe distance of mines from antiquities of Rome to prevent "damage caused by pozzolana quarries."[181] This problem persisted well past the sixteenth century as Fea lamented, "how many have dug into foundations, simply to obtain pozzolana, making the buildings collapse shortly thereafter!"[182] The heavy weight of the material and use in populated areas for construction and trade was due to the urban mines being the most economical. When the

180 Chandra Mukerji, "Tacit Knowledge and Classical Technique in 17th-century France: Hydraulic Cement as a Living Practice among Masons and Military Engineers," *Technology and Culture* 47, no. 4 (2006): 713.

181 Roberto Gargiani, *Concrete, from Archeology to Invention, 1700-1796: the Renaissance of Pozzolana and Roman Construction Techniques,* trans. Stephen Piccolo (London: Rutledge, 2013), 51.

182 Gargiani, *Concrete*, 61.

material was used in the city, the sand was transported by cart. “Pozzolana in Rome is measured by the cartful, the wagonload, or the sack,” writes Gargiani.[183] However, water transport was a far preferred method for bulk transportation over longer distances. This is why the port of Civitavecchia, just outside of the city, became crucial to the Mediterranean sand trade. Once the sands reached Civitavecchia, another calculation was made. Although some ships could carry more weight, most of the sand was exported on small Italian *tartanas*.[184] These sea carriers likely conveyed around as much sand as could be transported on barges.[185]

Like pozzolans, German *tuffstein* was similarly available to the Dutch due to a catastrophic history of volcanic activity. As the massive ice sheets of the Younger Dryas melted, pressure alleviated on the European continent and a wave of volcanic activity followed. The largest associated eruption was the Laacher See explosion around 10,900 BCE.[186] In this massive explosion, pyroclastic lava flows dammed the Rhine River, but eventually gave way to the water that flows to the northern sea. The caldera still holds a large lake in what is now Germany. In a similar way as the Roman hydraulic cement production methods were maintained in France, the mixing of ground *tuff* stones in cements seemingly survived through oral histories and construction traditions only to be revived on a large-scale in the early modern period.

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183 Gargiani, *Concrete*, 52.

184 Gargiani, *Concrete*, 55.

185 Sierfele offers a calculation of the amount that could be transported at around 30 to 50 tons. See: Rolf P. Sieferle, *The Subterranean Forest: Energy Systems and the Industrial Revolution* (Cambridge: The White Horse Press, 2001), 98.

186 De Klerk, Pim, Wolfgang Janke, Peter Kühn, and Martin Theuerkauf. “Environmental Impact of the Laacher See Eruption at a Large Distance from the Volcano: Integrated Palaeoecological Studies from Vorpommern (NE Germany),” 270, no. 1 (2008), 196-214.

In 1777 an English aristocrat named William Hamilton described the abundance of these volcanic stones, which he observed on a yacht trip along the Rhine River from Bonn to Mayence. He wrote that, "on each side of the Rhine, most of the way from Bonn to Coblenz, particularly between Prohl and Andernach, I perceived high rocks of lava or tuffa."[187] "I must not forget to mention another curious circumstance: at Andernach, between Bonn and Coblenz," Hamilton continued, "I saw vast heaps of tuffa ready cut, lying on the banks of the Rhine, and some Dutch vessels loading it; upon enquiry I found that a considerable trade of this material is carried on between this town and Holland, where they grind down this sort of stone by wind-mills into a powder, which they use as a pozzolana for all their buildings under water."[188] This is a significant observation of the process of manufacturing *trass*. The stones were German, but it was the Dutch who exploited the resource as a building material in the North Sea trading zone.

Dutch *trass* was a viable substitute in the North Sea trade networks, yet it involved a more intensive production process than just digging sands as was the case with true pozzolans. It required grinding to be fit for use in hydraulic cements. The Dutch controlled inland transportation by river that gave access to, among other goods, the German *tuffstein*. The Dutch had imported these volcanic stones along the Rhine since at least the sixteenth century. Gargiani described, "the rocks are removed in pieces and transported with carts to Andernach or Brohl, for river shipping."[189] He also recorded

187 "A Letter from Sir William Hamilton, K.B.F.R.S. to Sir John Pringle, Bart. P.R.S. Giving an Account of Certain Traces of Volcanos on the Banks of the Rhine," in *Philosophical Transactions of the Royal Society of London* (1676-1678), 4.

188 "A Letter," 4.

189 Gargiani, *Concrete*, 64-65.

inspectors that would “examine the stones when they reached Holland for the proper quality.”[190] Much like the Tiber River discussed above, the Rhine provided a way to transport these bulk materials to the lowland delta. This rounded out the materials that were available to all.

Hydraulic cement was used extensively in canal projects across Europe during the early modern period.[191] The most significant canal of the early modern western European pozzolan revival was the 240 kilometer long canal that connected the Mediterranean to the North Atlantic in a path through western France.[192] Pierre Paul Riquet was put in charge of the project’s construction. His position demonstrated a period before building was captured by professional organizations. Like King Phillip II, Riquet’s privileges were bestowed and not earned. He first married into money. Then, as a noble, he benefited from the nepotism of the absolutist state. This bequeathed him a position as a tax collector in Languedoc, a province in west-central France. Riquet continued the state mission to squeeze revenue from the salt trade dating back to the thirteenth century.[193] Beyond enriching himself by the fruits of other people’s labor, he also surveyed the land as he went door to door to collect his ill-gotten gains. This gave him familiarity with the countryside where the canal would soon pass. Riquet had no formal training in engineering and as Mukerji observed, it was “easier to conceive of plans for cutting a

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190 Gargiani, *Concrete*, 69.

191 Historian Charles Hadfield documents the ancient origins of canal locks in China and continental canals that were built during the 11th and 12th century. He argued that the canals of Great Britain were based off of the swinging gate model of Leonardo da Vinci. Charles Hadfield, *The Canal Age* (London: Pan Books LTD, 1971), 3.

192 Rolt, *From Sea to Sea*, 13.

193 Rolt, *From Sea to Sea*, 19-22.

canal across Languedoc than to engender public trust in Pierre-Paul Riquet."[194] Riquet was in luck. Public trust is rarely a requirement for major engineering projects. The canal was funded by the monarch and completed by 1681.

The canal embodied the mercantile practice of maximizing state power through a positive balance of trade. No figure personifies the wedding of state power and mercantile economics more than *le Roi Soleil*, or the Sun King, in France who commissioned the project. King Louis XIV, who ruled from 1643 to 1715, was a prototypical absolutist monarch, one who was mercantile, ambitious, unaccountable and lavish. Between 1661 and 1683, the expansive economic growth under the Sun King was due in large part to the efforts of the regal's minister of finances, Jean-Baptiste Colbert. In addition to promoting the construction of roads and other internal improvements, Colbert patronized the building of the Canal du Midi, the most significant civil engineering work during King Louis XIV's tenure. Mukerji expands on the mercantile logic behind the canal's construction by stating that King Louis XIV and Colbert "assumed that political power would lead to riches, not the other way around."[195] Due to this outlook, the canal was built to be wide enough for warships to "obviate a long sea passage and therefore had to be designed to pass the seagoing craft of the day."[196]

The Canal du Midi is significant in the history of building in western Europe not only due its size, but due to the materials that were used in some of its aqueducts, locks and seawalls. It was the first major hydraulic work that extensively used pozzolan cement

194 Chandra Mukerji, *Impossible Engineering: Technology and Territoriality on the Canal Du Midi* (Princeton, N.J: Princeton University Press, 2009), 5.

195 Mukerji, "Tacit," 716.

196 Rolt, *From Sea to Sea*, 21.

since the age of the Roman Empire. Even though much of the canal's infrastructure was made of pounded clay and timber, pozzolan cement was used for significant pieces of the project. An indication of the innovative revival of pozzolan cement in hydraulic building for the canal can be seen in the construction of a seawall at Sète, on the southern terminus of the canal. Mukerji explained that, "Riquet imported Pozzolana from Italy in 1670 for Sète, apparently eager to make use of its unusual properties."[197] "Colbert was not impressed," she continued. Perceiving that Riquet's inexperience led to this non-traditional building material, Colbert "later made it clear that he was dismayed rather than pleased by the news; he was convinced that Riquet's use of cement was simply a way to cut the costs of quarrying and stonecutting that would lead to failures."[198] Riquet blended traditional cut stone facing and hydraulic cement to finish the seawall, thereby settling the controversy.[199] Riquet's use of pozzolana cement clearly departed from the dominant engineering wisdom of the day and broke free from traditional building methods. Partly due to this and other successes of the seventeenth century, France became a major importer of Italian pozzolans—increasingly used for hydraulic engineering projects in the country throughout the next century and a half.

Mukerji cautions the reader not to view this as a cleavage from the distant past, however. She writes that, hydraulic cement's "'rediscovery' in the eighteenth century was assumed to be a recovery of a lost art, but was really part of a longer process of

197 Mukerji, *Impossible*, 123.

198 Mukerji, *Impossible*, 123.

199 Mukerji, "Tacit," 725.

reproduction and formalization."[200] This was due to the continued use of the Roman methods, knowledge of which was passed down through oral history and as trade secrets. The recipe for pozzolanic cements was not written down, as Mukerji observed, until the 1690s when French engineer Marquis de Vauban recorded the mixture in a letter.[201] Nevertheless, the methods can be traced back to the ancient Romans and the words of Vitruvius centuries before. The conditions for another period of widespread use of volcanic sands for hydraulic mortars mixed with pozzolans did not return until the major hydraulic construction projects of the early modern period to which the Canal du Midi belongs.

There was also a geographic connection as the southern coast of France was near the supply hubs on the western edge of the Italian Peninsula. France was a significant importer of such sands, but not the only one. Architectural historian Roberto Gargiani documented the widespread use of Italian pozzolans throughout the Mediterranean World by the eighteenth century where deliveries arrived in Italian ports that include Genoa, Leghorn, Ancona, Pesaro, Ramini and Malamocco; European nations that included France, Spain and Portugal; as well as Malta, the Levant and North Africa were importers as well.[202] The Catholic Church held a near monopoly on supplying Italian pozzolans by the early modern period. Its main papal port was Civitavecchia, located 80 km north of Rome on the west coast of the Italian peninsula. According to the contemporary French

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200 Mukerji, "Tacit," 713.

201 Mukerji rightly observed that since Vitruvius did not explicitly record the formula, Vauban was likely the first to put it into writing. See: Adge, "L'art de l'hydraulique, 202-3. Reproduced and translated in: Mukerji, "Tacit," 715-716.

202 Gargiani, *Concrete*, 54.

observer Jean Baptiste-Francois Vidau, the main trade of the port by the eighteenth century was the "perfect red earth for building under water."[203] This was partially due to the geographic advantage related to its close proximity to the same sands used in ancient Rome.

Although the sands could be imported, the French still had to rely on the whims of the exporters. This created a dependency lamented by many. In 1724, French clergyman and traveler Jean-Baptist Labat complained that, "we French always have to go get [pozzolana] in Italy."[204] He recorded that the peninsula was rich with these sands and "it is an error to believe that it exists only in Poussol near Naples, it is everywhere in the Roman countryside."[205] This was part of an ancient tradition of supplying the sands around the city. Historian Gargiani writes that, "only in rare cases was it possible to purchase pozzolana unloaded from boats arriving from Naples at Civitavecchia."[206] Instead, the sand was mined in Rome and transported using the Tiber River. The urban sands were primarily carried in shallow hull keel boats "towed by men or animals along special trails on the banks."[207] From there, the boats would reach Civitavecchia, a few kilometers north of the river's mouth.

This proves the continued defining features of transportation and resource proximity to the economy of cement production and application, a point that Labat

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203 Gargiani, *Concrete*, 58.

204 Gargiani, *Concrete*, 61.

205 Gargiani, *Concrete,* 58.

206 Gargiani, *Concrete*, 51.

207 Gargiani, *Concrete*, 54.

misunderstood. He, and many others, were aware that similar sands could be found throughout the French colonies.[208] For example, a French dictionary entry from 1751 recorded that "the term [pozzolana] refers to a type of sand found around Pouzzol of Italy, near Naples; it is also found in Guadaloupe, in Martinique, and the Isle of France [or Maritius]"[209] Labat proposed that, in order to end reliance on Italian pozzolana, all French ships from colonies with volcanic sands should return with the material as ballast weights.[210] This would have required a trade-off, however. Extracting resources from the colonies required transporting goods to the home port. Loading ships with sand would have reduced the amount of goods that could have been taken from such regions. In the logic of colonial trade, exporting bulk materials for ballast weight was the only practice that made sense. Labat also overlooked what is a recurring theme in this study, that the presence of a resource is not enough for its widespread exploitation in building. Feasibility of transportation, energy, and cultural factors were each important determinants of the trade zones of sand and who could, and did, access them.

Conclusion

The deep history of cement production in western Europe provides the socio-technical context from which the modern global cement regime emerged. Although *Homo sapiens* have burned calcium carbonate for roughly 12,000 years, the Roman Empire fulfilled the necessary conditions for the first cement transition. Imperial access to resources and the demand for building on land and sea overlapped with a geological

208 Gargiani, *Concrete*, 58-62.

209 Gargiani, *Concrete*, 61.

210 Gargiani, *Concrete*, 61.

endowment of calcium carbonate and volcanic sands. For millennia, cement made from such materials determined the possibilities of hydraulic building in western Europe. It also conditioned builders and boosters to the use of anthropic stones. The Roman example also demonstrated the energy dynamics of all cement production in western Europe prior to the Industrial Revolution and oft-times after. Trade-offs between dedicating land to firewood and timber while also sustaining agriculture was a persistent problem for all societies that produced lime in the organic economy. Although firmly within this western European building tradition, the British changed the dynamics by substituting coal for firewood. Nevertheless, the use of such building materials would have looked significantly different without the material inheritance of the Roman concrete regime.

CHAPTER THREE

LIME

Introduction

"It is one of the peculiar blessings among others conferred by Providence on the British Isles that in addition to the abundance of food and other produce obtained from the land, the bowels of the earth send forth great riches, arising from iron, copper, lead, tin, salt, allum, coals, stones, lime, chalk, slate, and various other articles," Patrick Colquhoun, a Scottish merchant, wrote of Great Britain's attributes in 1814.[211] The most transformative of these riches included coal, lime(stone) and chalk. Beginning in the thirteenth century, British lime burners exploited this fossil endowment to manufacture lime outside of the organic economy. By the time of Colquhoun's writing, lime produced with coal was used for dyes, to tan hides, to dissolve waste, for medical procedures, to catch birds, purify coal gas, as a flux for metal, as an interior and exterior plaster and for many other purposes.[212] An encyclopedia article from 1845 recorded that "lime is exported in vast quantities from Bristol to the West Indies for the purpose of sugar refining."[213] Most significantly, lime was used by the British as a building material and agricultural supplement. This helped the British avoid environmental limits in the

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211 Patrick Colquhoun, *A Treatise on the Wealth, Power and Resources of the British Empire in Every Quarter of the World, Including the East Indies*, 2nd ed. (London: Printed for Joseph Mawman, Ludgate Street, 1815), 67.

212 *Encyclopaedia Metropolitana*, vol. 20, eds. Edward Smedley, Rev. Hugh James Rose and Henry John Rose (London: B. Fellows and J. Rivington, 1845), 28; Charles Hunt, *A History of the Introduction of Gas Lighting* (London: Walter King, 1907), xxxvi; and T. L. Donaldson, "Stucco," in *Encyclopaedia Metropolitana*, vol. 25, eds. Edward Smedley, Rev. Hugh James Rose and Henry John Rose (London: B. Fellows and J. Rivington, 1845), 151.

213 Donaldson, "Stucco," 151.

centuries prior to the Industrial Revolution. To borrow a phrase from Colquhoun's contemporary David Ricardo, the fossil endowment provided the island-nation a unique comparative advantage.[214]

This fossil advantage has long been recognized by historians in relation to coal. Large deposits of the fossilized carbon existed across Great Britain. They had been exploited as a fuel source for at least half a millennium by the time of British industrial take-off in the early nineteenth century. Throughout this period, coal was utilized extensively in the lime industries that required heating calcium carbonate. Burning fossil materials with fossil fuels was a unique departure from all other global lime production from its origins in the 13th century well into the nineteenth century. Historian E.A. Wrigley again provides a useful framework for understanding this historical anomaly. He argued that mineral fuels, like coal, changed the dynamics of economies. Rather than organic fuels that rely on the flow of sunlight to regenerate through photosynthesis, "fossil fuels could provide access to a massive *stock* of energy." Although finite in quantity, Wrigley stressed that "the use of fossil fuels can provide an interlude during which exponential growth is possible."[215] The stock is depleted over time and does not have a regenerative cycle relevant to the human lifespan, but could sustain intensive energy demand—while supplies lasted. This too could be considered the case with calcium carbonate. The fossil material existed in even larger abundance in Great Britain and was also free from the trade-offs associated with the organic economy. The pairing of

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214 David Ricardo, *On the Principles of Political Economy and Taxation* (London: Electric Book Co., 2001).

215 E. A. Wrigley, *The Path to Sustained Growth,* 18.

these two fossil riches allowed for the production of a material that was free from the boundaries of the organic economy.

Wrigley also understood the unique characteristics of British demographic and economic growth in the centuries leading up to the Industrial Revolution. During this period, between roughly 1600 and 1800, agricultural output per acre and urban growth actually increased in tandem.[216] This was atypical in agrarian societies. Anthony Wrigley reconciled this feature by describing the early modern British as achieving "an advanced organic economy" where increased agricultural yields met the needs of a large non-agricultural population.[217] He explained that "in 1800 the comparative prosperity of England reflected in large measure the scope for advance within the context of an organic economy rather than the fruits of a new era."[218] Wrigley acknowledged that although the British had not departed from an organic economy, the dynamics of the British system demonstrated unusual features. Historical consistency is stressed in his analysis that assumes the British were barreling towards an economic and demographic ceiling prior to their transition to a mineral economy during the Industrial Revolution. It is impossible to know if the British were about to reach environmental limits in the early modern period, but many indicators hinted otherwise.

Wrigley's conclusion is skewed by a focus on coal. When calcium carbonate is added to the mineral equation, it could be argued that, starting around 1600, the British had become a proto-fossil economy—one where fossil fuels and fossil materials were

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216 Wrigley, *Continuity,* 35.

217 E. A. Wrigley, "The Transition to an Advanced Organic Economy: Half a Millennium of English Agriculture." *The Economic History Review* 59, no. 3 (2006): 435–480), 457.

218 Wrigley, "The Transition," 478.

used to overcome environmental limits related to fuel, agriculture and building. This was evident in the uniquely urban character of early modern British society. Urbanization in Great Britain was far from preordained and did not occur in a vacuum. It was part of a general trend that occurred across Europe beginning in the late Middle Ages and continued through the early modern period. Historian Jan De Vries carried out a large demographic study of this phenomenon and summarized that, "while urban Europeans did not become relatively more numerous, they did become concentrated in fewer cities. Between 1600 and 1750 the number of cities over 100,000 grew from eight to thirteen; those in northern Europe grew from two to six."[219] This urban growth had global historical significance. At the start of the fifteenth century, Paris was the only European city in the top ten largest cities worldwide. By 1800, there were four.[220] There was an intra-European urban realignment that occurred at this time as well. In 1400, England, Scotland and the Low Countries contained three of the top 100 cities in Europe. By 1800, that number was at twenty-three.[221] Of these regions, England had the most. Wrigley documented the rise of English cities where "on the continent the number of towns with between 5,000 and 10,000 inhabitants actually fell between 1600 and 1750; in England the number doubled."[222] During the same period, London's population increased from

219 De Vries, *The Economy of Europe in an Age of Crisis, 1600-1750* (Cambridge: Cambridge University Press, 1976), 154.

220 Tertius Chandler, *Five Thousand Years of Urban Growth: A Historical Consensus* Lewiston: St. David's University Press, 1987), 566.

221 Chandler, *Five Thousand*, 18-23.

222 Wrigley, *Continuity,* 15.

200,000 to 675,000.[223] By 1801, Greater London had reached one million inhabitants, only achieved in the West by ancient Rome.[224]

This British urban ascendancy was directly related to the environmental possibilities afforded by the fossil endowment. At first glance, Great Britain seems like a poor location for such a pre-industrial urban transformation. Located in the northern latitudes, the extreme climactic conditions of the Little Ice Age limited growing seasons. Year-round precipitation inundated soils with moisture, which were unfit for most agriculture. The isle of Great Britain had limits to land as well. Any of these factors could have stunted economic and demographic growth, if not ended it outright, in the organic economy. This was due to the trade-offs between dedicating land to agriculture or firewood and building timber. As was demonstrated in the ancient Roman example, increases in the area allotted for one type of land use generally meant decreased land availability for the other. Yet, the British never hit Malthusian limits related to food or construction. This was largely due to the production of lime outside of the organic economy. The material allowed for production of cement in a central location, like the City of London, without the need for firewood from the surrounding countryside. It also neutralized the soggy and damp soil while simultaneously improving nutrient uptake in plants when mixed with manure. Finally, it provided a fire-resistant and inorganic substitute for building in the capital city. The fossil advantage simultaneously required

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223 E. A. Wrigley, "Urban Growth and Agricultural Change: England and the Continent in the Early Modern Period," *The Journal of Interdisciplinary History* 15, no. 4 (Spring, 1985), 688.

224 Chandler, *Five Thousand,* 13.

less land be set aside for timber while increasing the area of land that could be dedicated to agriculture as well as its productivity.

Due to the abundance of these fossil resources, early modern Britons were awash with lime. This was due to their ability to increase production exponentially by drawing from the stock. Had copious amounts of lime not been available for use in agriculture and building, it is possible that the British would have reached limits to demographic and economic growth long before the technological breakthroughs associated with the Industrial Revolution. The increasingly urban character of British society was also related to the possibilities afforded by producing copious amounts of lime outside of the organic economy. The lowly British lime-burners accomplished the first instance of sustaining urban population growth outside of the organic economy. The liberal application of lime produced with coal on the soggy soils expanded agricultural possibilities thereby affording more land and increasing yields per hand. That feature fed urban populations with laborers not dedicated to agriculture whose habitat was also built from the stock. Although the brick and mortar buildings of the proto-mineral economy were not built to last, they were the monuments urbanization outside of the organic economy.

Fossil Advantage: Urban Industry

Two and a half centuries prior to Colquhoun's observations, the English priest William Harrison noted the resource wealth of Great Britain in his 1577 *Description of England*. "Of coal-mines we have such plenty in the north and western parts of our island as may suffice for all the realm of England; and so must they do hereafter indeed, if wood be not better cherished than it is at this present."[225] He continued, "besides our coal mines, we have pits in like a sort of white plaster, and of fat and white and other coloured marble."[226] These calcium carbonate deposits were equally abundant and, when made into cement, also provided an inorganic substitute for building. By at least the 13th century, British builders had altered the socio-technical features of the western European building regime by producing cements from the island's unique fossil endowment.[227] This was the first instance of producing a building material outside of organic limits and, although often overlooked, was an important point in the history of building materials. As with the addition of pozzolan by the Romans, the British cement made in the fossil economy significantly changed the material's production possibilities. Also like the Romans, this production method was possible due to the geographic good fortune of having access to seemingly inexhaustible stocks of fossil fuels and fossil materials. The first noticeable feature of the British fossil advantage included the ability to produce lime in a central location free from the trade-offs of thermal industries in the organic economy.

The origins of the British method of burning calcium carbonate with coal is unknown. Lime was used as a cementitious building material since the Middle Ages, however. The architect George Godwin noted that the "the Normans often constructed buildings entirely of rubble stone or pebbles, rendered into a mass by lime; nearly all

225 William Harrison, *William Harrison's Description of England in Shakespeare's Youth,* edited by Frederick J Furnivall (London: Trubner and Co., 1877), Ch. XI, https://sourcebooks.fordham.edu/mod/1577harrison-england.asp.

226 Harrison, *William Harrison's*, Ch. XI.

227 Nef, *The Rise,* 5-6.

their edifices have some parts so formed."[228] Indeed, many such masses of bonded stone existed across the island at the time of Harrison's writing. He marveled that "the common schools of Cambridge…,the kings chapel in Cambridge,…with the Chapel that King Henry the Seventh did build at Westminster, there are not (in my opinion) made of lime and stone three more notable piles within the compass of Europe."[229] These structures were built using stone and cement, likely produced with coal, well before the Elizabethan Age. Energy historian John Hatcher noted that these "large-scale building works, where lime was used primarily for mortar and for plaster, provide us with many of the most spectacular examples of medieval coal consumption."[230] Regardless of the precise date of when that practice began, it occurred at an early date.

Harrison built his narrative from a predecessor named Leland whose observations were made fifty years prior. These descriptions of British building included accounts of a wide range of building materials that differed from location to location. Some British towns had buildings of timber. Others had buildings of stone. There was little mention of brick, besides that recycled from the Roman period. The clergyman travelled the country crossing bridges of stone and timber as well. Leland understood these British structures to be cutting edge. He suggested that prints depicting British buildings, "if well design'd, cut in Copper Plates, and printed off, would possibly prove an acceptable Work, which to the Honour of the Nation would shew the World that we are not inferior to our

228 George Godwin, "Prize Essay Upon the Nature and Properties of Concrete, and its Application to Construction up to the Present Period," in *Transactions of the Royal Institute of British Architects*, vol. 1 (London: John Weale, 1836), 9.

229 Harrison, *William Harrison's*, Ch. XVIII.

230 John Hatcher, *The History of the British Coal Industry* (Oxford: Oxfordshire: Clarendon Press, 1900), 22.

Neighbours and others in magnificent Buildings either Publick or Private."[231] This claim would have been laughable in the seventeenth century as the great architectural centers of Europe were in France and Italy. It is interesting to note, however, that before the architectural departure that will be discussed below, the British allowed for a robust Medieval building tradition.

Despite being overlooked by Leland, brick and mortar building increased on the island alongside the general trend across Europe and was well underway at the time of his writing. Materials historian Norman Davey wrote of the spread of this building matrix in the 13th century throughout Europe as "a result of this close intercourse between Venice, Flanders, and England the craft of brickmaking and other building crafts, and the use of more or less uniform size of brick, eventually became common throughout the whole of Europe before the end of the thirteenth century from North Italy to the Low Countries and East Anglia."[232] Organic resource scarcity was not what drove the early British brick and mortar building. It is true, as historian Michael Flinn pointed out, brick and mortar "became the normal material for the construction of even the most humble dwellings in the south-east and East Anglia, and it spread to areas previously dominated by timber-frame construction and where stone was unavailable."[233]

The reason for this materials transformation is less clear cut. Flinn identified, "a lack of good timber and stone, and supplies of soil suitable for brickmaking."[234] There

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231 John Leland, *The Itinerary of John Leland the Antiquary,* 3rd ed., vol. 1 (Oxford: Printed at the Theater for James Fletcher, Bookseller in the Turl; and Joseph Pete, Bookseller at Eaton, 1744), 172.

232 Norman Davey, *A History of Building Materials* (New York, Drake Publishers LTD., 1971), 80.

233 Michael Flinn, *The History of the British Coal Industry*, vol. I (Oxford: Clarendon Press, 1993), 451.

234 Flinn, *The* History, 451.

was certainly good soil for brick making in these areas. There was access to timber and stone too. London, for example, had imported stones from the Isle of Portland since the 13th century and also imported stones from northern France.[235] Historian Robert Albion suggested that Great Britain remained heavily forested until the reign of Henry VII. He quoted one fifteenth century verse on the topic, "no lack of timber then was felt or fear'd; In Albion's happy isle."[236] On one hand, material scarcity is not an obvious driver of this building material shift.[237] On the other hand, the ability to fire materials with coal and the soils suitable for brick making did facilitate a robust British brick and mortar industry from an early period.

Brick and mortar produced in the fossil economy had particular advantages. Despite Great Britain being heavily timbered in the Late Middle Ages, the amount of firewood needed to burn lime was significant. One specific example was provided by Historian Louis Francis Salzman who found that "the Hundred Rolls of 175 complain that the king's two lime-kilns (*rees calcis*) had devoured 500 oaks between them."[238] Forests for lime was the trade-off if organic fuels were relied upon on the island of Great Britain. In time, maintaining intensive production of materials in the organic economy would have proved difficult. A firm estimate for the amount of wood fuel necessary to

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235 Harvey, *Mediaeval*, 110.

236 Albion, *Forests and Sea* Power, 121.

237 This is a significant addition to the scholarship that considers timber scarcity as a shaper of British technology. A shortage of firewood or building material does not seem to be the determinant of the switch to brick and mortar produced with coal. Flinn, "Timber and the Advance," 109-111.

238 L. F. Salzman, *Building in England, Down to 1540; a Documentary History* (Oxford: Clarendon Press, 1952), 150.

create a specific amount of lime in pre-industrial Great Britain does not exist. Historian John U. Nef provided an approximation. He observed that "on an average, about four [wagon]loads were used at Droitwich in the [fifteen]'seventies to reduce brine water to a tone of salt, and at least as much had to be provided to burn the limestone to make a ton of lime."[239] Based on this estimate, it would take two wagon loads to carry a trunk and possibly the entire tree, which meant roughly two trees per ton of lime produced. Therefore, the kilns for the Wellington works must have produced roughly 250 tons of lime. Although written centuries after fossil fuels were first utilized in the lime industries of Great Britain, Burnell identified various fuel substitutes and their associated requirements in lime production in this breakdown: "in order to produce 35 cubic feet of lime in an intermittent kiln, 60 cubic feet of oak; 117 cubic feet of fir; 9 cubic feet of coal; 117 cubic feet of peat."[240] Regardless of the specific numbers, as historian John U. Nef concluded, "it is evident that every increase in the quantity of bricks or saltpeter, lime or salt manufactured with wood fuel involved serious new encroachments upon native timber supplies."[241]

Coal substitution provided a cheap and abundant alternative fuel source. Burning fossil materials with fossil fuels differed from nearly all other cement production in time and space due to creating a material produced outside of the organic economy. Although brick clamps, frames, scaffolding and structural supports were still all provided from timber, British fossil cement was the first building material to not require organic fuels

239 Nef, *The Rise*, 193.

240 Burnell, *Rudimentary Treatise*, 35.

241 Nef, *The Rise,* 193.

for production. When used along with bricks produced with coal, this changed the relation of building materials to the environment.

British lime burners substituted mineral fuels for organic fuels very early on. The practice appears to have been well underway by the thirteenth century. Salzman also documented the use of coal in British cement industries at the same time that forests were being sacrificed to build castles. He wrote that "it was soon found that pit coal was the best fuel for the purpose, and it was constantly used from the end of the thirteenth century onwards, as much as 1166 quarters of sea coal being bought in 1278 for the kilns (*chauffornia*) in connection with the work at the Tower."[242] As early as the thirteenth century then, coal was being used to produce cement for large-scale construction projects. This was a significant departure from building on the continent where production was carried out with biofuels.

Not surprisingly, the most successful commercial kilns seemed to have been those located near coal deposits. Salzman observed that, "where lime was burnt commercially, that is to say for sale and not merely for use on the spot, the kilns would naturally be larger and more permanent, and a sixteenth-century account of the erection of eight such kilns at a place unnamed—probably Calais—shows that each kiln was 20 feet high, with walls 10 feet thick, and an average internal breadth of 10 feet, and cost over £450."[243] Rather than the temporary projects of the crown, the large static kilns served as a market for coal merchants as well. Locating such kilns, as well as brick manufacturing, near coal supplies afforded a seemingly endless supply of cheap fuel. This feature facilitated

242 Salzman, *Building in England,* 150.

243 Salzman, *Building in England,* 90.

intensive production along the "limestone belt," or midlands, where significant production and use of fossil cement occurred in the Late Middle Ages.

It deserves mentioning that there was also a unique property relationship that many English lime burners held with the resources they produced. Rather than control resources, the English Crown promoted the private use of raw materials. Harvey observed of this orientation of the British government that "they [the British ruling class] preferred to gather rents."[244] By the Elizabethan Age, this manifested in a 1568 ordinance that dictated "that by the law all mines of gold and silver within the realm, whether they be in the lands of the Queen, or of subjects, belong to the Queen by prerogative, with liberty to dig and carry away the ores thereof, and with other such incidents thereto as are necessary to be used for the getting of the ore."[245] Gold and silver were the only resources monopolized by the Crown and even this codification of resource law only came after centuries of resource exploitation by individuals. This system of resource management led increasingly to a situation where, as building materials historian Harvey observed, "the English quarryman was a local native who owned or leased the quarry rights in a particular place, and was experienced in the extraction of that kind of stone."[246]

Nevertheless, much of the lime-burning was still done by subcontracted laborers during the Middle Ages. "At Rochester castle in 1367-9 John Walsh was paid….for

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244 Harvey, *Mediaeval Craftsmen*, 113.

245 Donald N. Zillman and J. Russell Tyler, "The Common Law of Access and Surface Use in Mining," *Journal of Mineral Law & Policy* 1, no. 2 (1985-1986), 269.

246 John Harvey, *Mediaeval Craftsmen*, 113.

producing just under 3,000 quarters of mortar," for example.[247] As discussed in the previous chapter, the lime-burner was responsible for knowing how to burn a regionally specific calcium carbonate deposit, but was often dependent on contractors for fuel and transportation. This is a unique occurrence of specialization that was related directly to the changing relationship of the British laborer to the land. One specific example that demonstrated this connection between the skill of the lime burner and specific mineral deposits was displayed in the 15th century. Harvey provides a description of a building contract made on June 5th, 1495 between the Prior of Christ Church, Canterbury and lime burner William Denny "to burn lime at a kiln of the prior's beside St. Sepulchre's."[248] Harvey's description noted:

> For the burning of every 112 quarters of lime, the Prior was to find 152 bushels of sea coal by the heap; and every quarter of lime was to be 8 bushels by the heap. Denny was to dig chalk at his own pit, but the Prior was to provide carriage to the kiln, which Denny was to dig at his own cost—that is after burning the lime, he was to dig it out of the kiln without extra charge.[249]

Denny was clearly valued for his skill in producing the lime, but, beyond digging and burning, the transportation of materials and fuel acquisition were the responsibility of the Prior funding the project. This is a very specific example, but it highlights the reason why the British lime burner was not a completely independent manufacturer of a valued construction material. As discussed above, the transportation was significant at all phases of production. Property owners had the means and materials and the lime burner had the

247 Hatcher, *The History,* 426.

248 Harvey, *Mediaeval Craftsmen*, 114.

249 Harvey, *Mediaeval Craftsmen*, 114.

skill. It was an early instance of the leverage gained by the ownership of the means of production and transportation.

Lime manufacturing in London proved particularly advantageous due to this system of fossil material production. The fossil advantage provided the ability to produce cement in a central location without the trade-offs of the organic economy. Historians generally agree that, by the Elizabethan Age, Londoners had largely transitioned to the use of coal in homes and industries. There remains debate over whether the use of fossil fuels in the city was due to the abundance of coal or a dearth in firewood.[250] The use of coal in London's lime kilns preceded the period where firewood shortages, and related price increases, have been argued to have occurred. Lime industries in the city transitioned much earlier and clearly before any possible firewood shortages existed. Coal was used to produce cement in London at least as early as the examples discussed in the previous section.[251] From the 13th century forward, mineral cement and bricks made with coal were used extensively in the city. This provided a structural building matrix that did not require firewood and only necessitated timbers as support beams, thereby reducing the amount of land around the city that needed to be dedicated to growing wood. This was the earliest example of the ability to sustain the production of anthropic stones in a central location over time without the trade-offs of the organic economy.

This advantage must have been realized very early on by London's lime burners who have an ancient past. The city was served by its connection to the coastal trade. "Despite being over 300 miles from the collieries of north-east England, London was

250 Flinn, "Timber and the Advance," 117.

251 Nef, *The Rise,* 6.

favored with direct water communications," wrote energy historian John Hatcher, "and in the course of the thirteenth and fourteenth centuries references proliferate to merchants and shipowners making plans and securing licenses for the shipment of coal to the capital and other east coast ports."[252] Notable sources of chalk also existed in the Thames Basin along the shorelines of Kent and Essex.[253] Northeastern coal and southeastern calcium carbonate provided the raw materials for the lime industries in the city. This history is recorded in the street names as Harvey observed, "by 1228 there was already a place just outside the walls of London known as Sea Coal Lane, near Ludgate, where the coal was used for firing for lime kilns; the lane actually had the alternative name of Lime-burners' Lane."[254]

Although these materials afforded the ability to build from the stock, there were still sacrifices associated with lime's production. Burning low quality chalk with cheap coal in a densely populated area created a pronounced nuisance. Environmental historian Peter Brimblecombe observed that the reason why "we know that London lime-burners had become dependent on coal by the close of the thirteenth-century, for they were then viewed as the major source of air pollution, and were the objects of the earliest attempts to ban the use of coal on environmental grounds."[255] Historian William Te Brake uncovered that "a royal commission appointed in 1285 to inquire into the operation of

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252 Hatcher, *The History*, 25.

253 John Stowe, *Survey of London, Written in the Year 1598*, ed. William J. Thoms. (London: Whitaker and Co., 1842), 5.

254 Harvey, *Mediaeval*, 113.

255 Peter Brimblecombe, *The Big Smoke: a History of Air Pollution in London Since Medieval Times* (London: Methuen, 1987), 5-21.

certain lime kilns found 'that whereas formerly the lime used to be burnt with wood, it is now burnt with sea-coal.' Consequently, 'the air is infected and corrupted to the peril of those frequenting…and dwelling in those parts.'"[256] A similar commission investigated the kilns in 1288 "on complaint by many inhabitants that they are annoyed by the lime kilns."[257]

Legislation was drafted to address this noxious industry. For instance, in 1307, King Edward I issued a royal proclamation banning the use of sea coals as the produced "an intolerable smell [that] diffuses itself throughout the neighboring places and the air is greatly infected, to the annoyance of the magnates, citizens and others there dwelling and to the injury of their bodily health."[258] Many historians have commented on this occurrence, some going so far as to suggest that violators of King Edward I's restrictions on coal use in lime kilns were hanged.[259] Although the hanging cannot be verified, the early attempts to regulate coal use in the urban lime kilns is illuminating.[260] Despite the pollutants associated with burning lime with Seacole in the city, it never ceased to be an important urban building material.

One way that the value of coal in the urban lime industry can be understood is by comparing this thermal industry to British iron. In *The Subterranean Forrest,* energy

256 William H. Te Brake, "Air Pollution and Fuel Crises in Preindustrial London, 125-1650," *Technology and Culture* 16, No. 3 (July 1975): 339.

257 Te Brake, "Air Pollution," 339.

258 Te Brake, "Air Pollution," 340.

259 Samuel Smiles, *Lives of the Engineers: Smeaton and Rennie* (London: John Murray, 1904), 19.

260 Brimblecombe, *The Big Smoke,* 16.

historian Rolf Peter Sierfele's outlined the environmental demands of iron production as follows:

> An iron works made heavy demands on the environment: it had to be close to a deposit of ore to avoid costly transportation. It had to be near running water since it required water power to operate the bellows and hammer mills and because the product had to be transported by water to consumers. Therefore, the iron manufacturing industry was scattered over the countryside and as a rule did not operate near population centers, where wood provision would have been less convenient.[261]

Comparatively, mineral lime manufacturing had far fewer necessities. Since coal could be used as a fuel, it did not have the same relation to wood that would have been difficult to maintain in a city like London. Furthermore, burning lime and slaking it did not require the milling with water power. Finally, it had to be produced near the site of consumption so transportation of the finished product was less of a concern. Each of these factors made lime burning an early staple of the city.

The dynamics of London's lime industry also allowed it to avoid competing with resources needed for other purposes in the city. Reducing the amount of building timber needed in construction and not requiring firewood were two obvious examples. Another significant feature of this system involved the ability of lime to be produced with the lowest grade coal. When much of the city's inhabitants turned to coal for heating in the sixteenth century, the lime burners still used the low quality coal rejected for home use. Nef described this feature of mineral cement production when he observed that "in Pembrokeshire and the forest of Dean, 'riddlers' separated the output from the pits into

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261 Sierfele, *Subterranean,* 111-112.

‘fire’ coal, consisting of the largest blocks, ‘smith’ coal, and ‘lime’ coal.”[262] Smith and lime coal were the bottom rating in this system. “The smallest lumps,” Nef continued, “will serve for lime burning and the rounder will please the cook because they make a quick fire and constant heat.”[263] The benefits to the urban lime-burner were that the coal that was discarded for home heating and other industries could be used for producing the material, which helped ensure its longevity even after the growth in coal consumption associated with the Elizabethan Age.

Due to the unique features of the lime industries of London, it represents the longest continuous use of fossil fuels in urban industries as it provided the city with a fossil building material since at least the thirteenth century. Northeastern coal and southeastern chalk provided a unique fossil advantage to the city from an early date. London’s lime industry was not created because of any perceivable shortages, but also did not compete with firewood or building timber in the city. Even once many homes and industries switched to coal in the city during the Elizabethan coal transition, the lime kilns consumed the fuels rejected for other purposes. It did have an environmental cost as the noxious fumes were a constant irritant in the city. Despite the complaints of pollution from these urban lime kilns, the sustained production of anthropic stones continued unabated in this zone of increasingly intensive urbanization.

Fossil Advantage: Agriculture

The fusion of fossil fuels and fossil materials created another advantage related to the urban environment. In the organic economy, dedicating land to food production or

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262 Nef, *The Rise*, 112.

263 Nef, *The Rise*, 113.

use for fuel and building involved sacrifices between land uses.[264] Not only did British lime relieve pressure on the amount of land needing to be dedicated to wood production, it was also used to reclaim agricultural land and increased its productivity. Wrigley identified the connection between agriculture and urban growth as a positive feedback loop where urban populations were supplied almost entirely with domestic food supplies and their growing caloric needs stimulated agricultural growth.[265] Great Britain seems like an unlikely place for agricultural-urban success in the early modern period. A relatively cold climate, damp soils and limited land disadvantaged the British agriculturalist. Nevertheless, between 1600 and 1800, British agricultural productivity increased per person and per acre in a process that Wrigley called “the single most remarkable feature of the economic history of England” at that time.[266] This success of the British improver has often been described in relation to the Second Agricultural Revolution where land reclamation, improved plow technology, new crops, crop rotations and enclosures have all been put forward as causes for increased agricultural production during this period in Great Britain.[267] None of these innovations were unique to the soggy island and therefore do not explain why the British improver was the most productive

264 E. Anthony Wrigley. “Urban Growth and Agricultural Change: England and the Continent in the Early Modern Period.” *The Journal of Interdisciplinary History* 15, no. 4 (1985), 683.

265 Wrigley, “The Transition,” 436.

266 Wrigley, “Urban Growth,” 725.

267 Mark Overton, *Agricultural Revolution in England: the Transformation of the Agrarian Economy, 1500-1850* (Cambridge: Cambridge University Press, 1996).

agriculturalist in early modern western Europe.[268] For that, one must turn again to the lime industry.

Various agricultural innovations could drain water from the land, increase tillage, conquer land and diversify crops. There still remained a fundamental problem with British agriculture that included low pH levels in the island's damp soils. This made the soil acidic and unfit for most domestic crops. Lime neutralized the soil while encouraging the uptake of nutrients in plants.[269] This increased both the land available for agriculture and the yields per acre.[270] It is difficult to quantify the precise gains of this early method of changing the possibilities of the soil, but the material was used extensively from the seventeenth century onward. It seems clear that without this agricultural supplement—produced largely in the mineral economy—the domestic agricultural surpluses that fed urban populations would have been severely stunted. A testament to the impact of agricultural lime involved the sustained population growth of London, which grew by 280 percent between 1550 and 1820 and was fed with domestic food supply during much of that time.[271]

The British fossil advantage was well-known to agriculturalists by the seventeenth century. Nef observed that "by 1600 it [coal] had become 'almost the universal fuel for

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268 Wrigley, *Continuity,* 35.

269 "Understanding Soil pH," last updated April 5, 2019, https://extension.psu.edu/understanding-soil-ph.

270 Donaldson commented on this practice in 1845, "it is most copiously employed in many parts of England as manure, improving those soils in which either sand or clay predominate, and greatly assisting and enriching manures which are all of animal or vegetable origin." Donaldson, "Stucco," 151.

271 Wrigley, *Continuity,* 13.

the innumerable lime kilns' that produced lime for mortar and for agriculture."[272] As Nef's observation suggests, urban building was only half of the story. In fact, it is only one third of the story when considering the amount of lime produced with coal on the island in the centuries leading up to the British Industrial Revolution. English lime kiln historian D.C. Johnson estimated that, prior to the widespread use of guano as fertilizer by the late nineteenth century, "almost two-thirds of lime produced in Britain was used on the land."[273] Flinn expands on his observation that "lime was used in building, too, but its principle use was agriculture. Its raw material, like brick-making, was widely available, but its consumption of coal tended to confine its location either on or very close to coal fields."[274] With the notable exception of East Anglia, which primarily relied on marl, the rest of the island had extensive accounts of liming the soil by 1800.[275] This provided a unique agricultural supplement.

A comparison of British agriculture to their western European counterparts demonstrates the unique advantage afforded by calcium carbonate and coal in the agricultural sector. The southern European countries had more temperate climate and soil that was productive for various crops. The northern countries did not. Great Britain and the Low Countries had to wage trench warfare against water to expand their agricultural capabilities. Historian Norman F. Cantor succinctly observed that, throughout much of the Middle Ages, many "areas facing the North Sea in the Low Countries, northern

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272 Nef, *The Rise*, 187.

273 David Johnson, *Lime Kilns History and Heritage* (Gloucestershire: Amberly, 2018), 20.

274 Flinn, *The History of,* 238.

275 H. C. Prince, "England Circa 1800," in *A New Historical Geography of England after 1600*, ed. H.C. Darby (Cambridge ; New York: Cambridge University Press, 1976), 116.

Germany, and eastern England were unusable marshlands."[276] Drainage was the primary way that the North Sea countries reclaimed land. The Dutch were famous for the windmills that pumped water out of their lowland republic.[277] They also dug ditches and built sluices to drain the alluvium of the large continental rivers. Agriculturalists in Great Britain replicated this process starting in the sixteenth century. "The clearing of the wood may have been the great epic of the Middle Ages," historian of British agriculture H.C. Darby wrote. "But now, after 1600 came other epics—the draining of the marsh, the reclamation of the heath, the enclosure of the arable,…and the beginning of the later seats of industry."[278]

Draining of the marsh and reclamation of the heath expanded the amount of land that could be dedicated to agriculture. The Dutch demonstrated what was possible in relation to land drainage. Historian John Richards estimated that "in total, 23,000 hectares of land had been drained for cultivation by 1800 in the Netherlands."[279] The British followed the lead of their neighbors from the Low Countries by draining much of East Anglia and other low-lying areas. Although there was considerable foreign influence in earlier drainage schemes, British agricultural historian Darby identified the General Draining Act of 1600 passed by parliament as a starting point for national dedication to

276 Norman F. Cantor, *Inventing the Middle Ages: The Lives, Works, and Ideas of the Great Medievalists of the Twentieth Century* (New York: Harper Perennial, 1991), 21.

277 Richards, *The Unending*, 55.

278 H.C. Darby, "Introduction," in *A New Historical Geography of England after 1600,* ed. H.C. Darby (Cambridge ; New York: Cambridge University Press, 1976), xiv.

279 Richards, *The Unending,* 55.

drainage schemes.[280]. Over the next two centuries, drainage projects increased across the island as more and more land was reclaimed from the swamp and the sea.

Drainage alone would not have sufficed in either Great Britain or the Low Countries. All of the northern European countries had to contend with damp soil. Water could be removed from the soil, but most domesticated plants require a neutral pH balance. In wet soil, the pH is often much lower. These soils are acidic. Once acidic soil is neutralized, an added benefit involves the increased uptake of plant nutrients. Prior to modern fertilizers and soil additives, this was accomplished through the use of calcium carbonate. The Dutch, Danish and English each used calciferous materials in the form of marl or lime made of chalk and limestone to solve this persistent problem.[281] Agricultural historian Eric Kerridge wrote "of all the extraneous fertilizers, lime, chalk and marl enjoyed the widest use."[282] Without it, none of the renowned agricultural improvements of northern Europe would have been possible.

The choice of agricultural supplements in the early modern period were determined by economy and availability. In Denmark, for example, marl was used as a building mortar and, during the eighteenth century, in agriculture.[283] This was typical in the Dutch Republic as well. Marl is a calciferous earth that functioned in much the same way as agricultural lime. It also had a few particular advantages. The first was that it did

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280 H.C. Darby, "The Age of the Improver," in *A New Historical Geography of England after 1600*, ed. H.C. Darby (Cambridge: Cambridge University Press, 1976), 33.

281 Thorkild Kjærgaard, *The Danish Revolution, 1500-1800: An Ecohistorical Interpretation* (Cambridge: Cambridge University Press, 1994), 49-50.

282 Eric Kerridge, *The Agricultural Revolution* (London: Allen & Unwin, 1967), 241.

283 Kjærgaard, *The Danish*, 51.

not require conversion using heat.[284] Marl existed as calciferous earth that could be mixed with the soil with no thermal conversion necessary. Therefore, it was free from the energy requirements of lime production. Second, it did not require supplies of calcium carbonate, which the continental countries facing the North Sea lacked.

Kerridge also explained the costs of using marl, "the longer the application of marls was persisted in, the further afield or deeper down had they to be sought…the necessarily increased costs roughly coincided with peculiarly diminishing returns, for repeated marling eventually defeated its own end, when the land was glutted and extra marl only lowered fertility, and what was needed instead was lime or manure."[285] Unlike their North Sea counterparts, the British avoided the diminishing returns and land sacrifices associated with marl by using lime produced in the mineral economy. The success of British agricultural lime was recorded by an early nineteenth century British farmer who was convinced that agricultural lime was "so infinitely superior to those of marl, that the last will in a short time cease to be used at all."[286] Abundant supplies of coal and calcium carbonate made widespread use of the superior soil supplement possible. If that lime production depended on firewood, there would be a negative feedback loop related to lime production and its use in agriculture. Any growth in one would reduce the available land for the other.

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284 Kjærgaard, *The Danish*, 128.

285 Kerridge, *The Agricultural*, 247.

286 Adam Murray, *General View of the Agriculture of the County of Warwick: With observations on the means of its improvement. Drawn up for the consideration of the Board of Agriculture and Internal Improvement* (London: B. M'Millan, 1815), 156.

When exactly the British first incorporated agricultural lime is unclear. Nef identified an early case where the “want of ‘sea coles’ is said to have caused a decay in the husbandry of Cambridgeshire as early as the reign of Henry VIII.”[287] The reason for this would have included its use for the production of agricultural lime. Regardless of the exact start date, it quickly became a significant feature of British agriculture during the Second Agricultural Revolution. “In country after country, after 1560, and still more after 1590,” Kerridge described of the spread of the system, “liming, or chalking, though not in itself an entirely new practice, grew so greatly in extent, frequency and volume, that it became effectually revolutionary.”[288] Regardless of the precise start date, the process of liming the soil seems to have been well-known and widely utilized by the opening of the seventeenth century.

Historian John Hatcher summed up the importance of lime to English agriculture succinctly when he wrote that, “we have only to read contemporary treatises in husbandry, and accounts of travelers or discourses of natural scientists, to be convinced that lime was becoming a product of rapidly increasing importance throughout the seventeenth century.”[289] Kerridge has shown that whereas it has been thought that British agriculture was transformed in the eighteenth and early nineteenth centuries, the transformation occurred by the start of the late sixteenth century and grew over time.[290] This aligns with the diffusion of liming technology. There is no specific quantification of

287 Nef, *The Rise*, 205.

288 Kerridge, *The Agricultural*, 248.

289 Nef, *The Rise*, 187.

290 Kerridge, *The Agricultural*, 207.

yields that the liberal application of lime afforded, but the domestic production of agricultural goods in early modern Great Britain would have been much reduced without it.

Even though the process was widely known in the seventeenth century, adoption of this new method for treating soils occurred at different places and in different times. One of the most detailed accounts of the process of diffusion comes from a 1681 account by British agriculturalist John Houghton. He wrote that,

> I think it is not impertinent to your business I to tell you, that in my opinion, a mighty improvement might be made of mossy - ground, in countries that abound with lime, above what is ordinarily known. He having accidentally set on fire about ten acres of mossy ground (which burned to the very sand) in the common belonging to W. sent his teams six or seven miles off (to Walfall) for lime, which he mix'd with the ashes, and sowed the plat of ground with rye, much against the opinion of his husbandmen, whose objections and jeers he could not otherwise silence, but by a peremptory command to hold their peace, and observe his order. And the issue was, that cho' he was constrained to make a costly fence about it, that crop of rye cleared all the charges of the fence, lime, feed, and husbandry, with advantage to his purse; and besides, turned a barren piece of moss into a good close of land.[291]

Although liming the ground may have been a new invention, the advantages were clear. Just as the husbandman saw the proof in the rye, on a large scale, the entire country witnessed that change by the end of the seventeenth century.

This method was also driven by boosters like Houghton who dreamed of expanding the wealth of Great Britain through improving the soil. "What advantages then might be made of some great mosses in Lancashire, and elsewhere, that lie near to coal and lime - stone, and therefore might well be spared, without making fuel dear, and improved at a very small charge, and for the present, yield little or no profit, save some

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291 John Houghton, *A Collection of Letters on the Improvement of Husbandry and Trade,* vol. 4 (London: Printed for Woodman and Lyon, 1728), 300-301.

grig, or heath for sheep, and young cattle to feed poorly, upon; and this oft in peril of their lives: particularly, what abundance of this sort of ground lies within a few miles of Clitherow (the great staple for lime) which is good for little or nothing in its present condition, but to make the country thin of inhabitants. Accept this at present from," he pondered.[292] Houghton only had to wait, as, over time, these regions developed agricultural surpluses that supplied industrial cities with foodstuffs. Arthur Young recorded his praises of the method in 1780 praises as the method had reached Ireland. He wrote that, "in general there is no ground worth 20s. an acre, that if you lime at 80 barrels, and take wheat, barley, and oats, it will then be worth 30s. This is certainly a marvelous improvement! Lord Doneraile knows, from an experiment of his brother's, that it is equally well adapted to boggy bottoms; he had five acres, which he let for 10s. 6d. the whole, and was so hard a bargain to the poor men, that an allowance was made for it. His brother took it, and limed it, and then mowed *five tons of hay per English acre*!"[293] Development on the island was directly related to the ability to alter the possibilities of the soil.

An example that demonstrates maldevelopment without such access to agricultural lime included the highlands in Scotland. Nef noted that, "in the highlands of Scotland, even in the eighteenth century, the farmers were forced to get along almost entirely without it [coal], owing to the excessive price, though they had the greatest difficulty in finding any other fuel with which to warm their huts, and had often to

292 Houghton, *A Collection*, 301.

293 Arthur Young, *A Tour in Ireland with General Observations on the Present State of that Kingdom Made in the Years 1776, 1777, and 1778. And Brought Down to the End of 1799,* vols. 1 & 2 (London: H. Goldney, 1780), 381-382.

perform their husbandry without any fertilizer because they had no peat or brushwood to spare for burning lime."[294] This is supported by contemporary accounts like Beaumont who wrote that "The lands in the Highlands abound in Lime stone, which are in great part nor lying uncultivated, and apparently to strangers barren, (as observed on other countries, until coal has been obtained on easy terms giving a scanty meal, and cold bed to the quadruped, will soon produce the necessities of life, with a genial warmth, and comfort to all its inhabitants."[295] The highlands were excluded due to their distance from the mineral endowment. Beyond what must have been an excruciating reality of being left out in the cold in a world increasingly reliant on fossil fuels, the lack of lime left them outside of the lime based agricultural realm of the rest of Great Britain.

The production and use of lime was plentiful across the island in the centuries leading up to the Industrial Revolution because it overcame the fundamental problem with British agriculture, poor soil. Over any other agricultural improvement, agricultural lime altered the possibilities of the perennially damp island. Rather than a static-state of traditional agricultural methods, the period between 1600 and 1800 saw the English alter the trade-offs of the organic economy with the unique fossil endowment. At a time when urban populations were fed with domestic foodstuffs, this was necessary for sustaining the growing populations in urban areas like London. Also, the improvement that lime afforded in agricultural productivity per person and per acre facilitated a large population not dedicated to farming. It is clear that liming the soil was a foundational process for making the land fit for domesticated crops. That increased food supply created a positive

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294 Nef, *The Rise,* 105.

295 Charles Beaumont, *Treatise on the Coal Trade* (London, J. Crowder, 1789), 32.

feedback loop with the nation's growing cities as buildings sprouted up alongside British crops.

Fossil Advantage: Urban Building

The growing populations lived in a habitat afforded by the fossil advantage as well. When Thomas More described utopia in his sixteenth century tract of the same name, he envisioned a world of densely populated cities moving away from timber construction. His description of the mythical capital of Amaurot reflected this view. "Their houses were at first low and mean, like cottages, made of any sort of timber, and were built with mud walls and thatched with straw," More explained of the island city. "But now their houses are three stories high: the fronts of them are faced either with stone, plastering, or brick…their roofs are flat, and on them they lay a sort of plaster, which costs very little, and yet is so tempered that it is not apt to take fire, and yet resist the weather more than lead."[296] It is not surprising that this was the view of the future from a Londoner in the 1500s. This was the start of a period when European urban populations increased alongside a building trend in major cities that substituted stone—both natural and anthropogenic—for timber in order to mitigate the risk of fire. These urban transformations were shaped by the environmental possibilities of the regions where they occurred. London's building materials transition was related directly to the fossil advantage.

The Great Fire of London demonstrated a persistent threat to all urban built environments. "2 September 1666," read admiral John Evelyn's Diary, "this fatal night,

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296 Thomas More, "Of their Towns, Particularly of Amaurot," in *Utopia* (1515), accessed June 6, 2021, https://www.marxists.org/reference/archive/more/works/utopia/ch3.html.

about ten, began the deplorable fire, near Fish street, in London."[297] He was describing London's Great Fire of 1666, which burned for three days and destroyed nearly everything within the old Roman walls. Evelyn described the aftermath, "I have seen 200,000 people of all ranks and degrees dispersed, and lying along by their heaps of what they could save from the fire."[298] The Great Fire of London demonstrated a universal threat to all densely populated areas. This threat was amplified by combustible building materials. Historian Samuel Smiles described the city of London prior to the catastrophe, "the population of the city was about 150,000, living in some 17,000 houses, brick below and timber above, with picturesque gableends, and sign boards swinging over the footways. The upper parts of the houses so overhung the foundations, and the streets were so narrow, that D'Avenant said the opposite neighbours might shake hands without stirring from home. The ways were then quite impassable for carriages, which had not yet indeed been introduced into England; all travelling being on foot or on horseback."[299] It was these half-timbered buildings in a cramped city that greatly contributed to the veracity of the fire.

The danger of such a built environment was obvious to all who considered such occurrences. Evelyn provided his own description of London before the fire. In 1659, he described it as "a City consisting of a wooden, northern, and inartificiall congestion of Houses."[300] He knew that fire was a threat to wooden cities across Europe, not just

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297 John Evelyn, *The Diary of John Evelyn*, vol. 2, ed. William Bray (New York: M. Walter Dunne, 1901), 20.

298 Evelyn, *The Diary,* 25.

299 Smiles, *Lives of the Engineers*, vol. 1, 62.

300 Evelyn, *Fumifugium*, prefatory note.

London. “In a word, not only here and there an house, but whole towns, and great cities are, and have been built of fir only; nor that alone in the north, as Mosco, &c. where the very streets are pav’d with it, (the bodies of the trees lying prostrate one by one in manner of a raft) but the renowned city of Constantinople; and nearer home Tholose in France, was within little more than an hundred years, most of fir, which is now wholly marble and brick, after 800 houses had been burnt, as it often chances at Constantinople,” wrote the British admiral. “Not heeding the warning, but where no accident even of this devouring nature, will at all move them to re-edifice with more lasting materials.”[301] The historian Eric Jones whose own work profiled the impact of fires as “social disasters” listed the tragedies that proved Evelyn correct as “in Constantinople 7,000 people died in a fire in 1729, 20,000 houses were burned down in 1750, 15,000 in 1756, 10,000 in 1782, and 10,000 again in 1784.”[302]

Fire, then was a driver for building with inorganic materials in cities. This was a primary driver of lithic building material transitions that, according to Jones, “spread across Europe in early modern times, greatly reducing vulnerability to fire, as well as simple wear and tear.”[303] Jones argued that the ability to mitigate fire’s destructive forces was a primary cause of the success of highly urbanized pre-industrial European societies.[304] He hypothesized that, uniquely prevalent in western Europe, lithic urban

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301 Evelyn, *Sylva*, 242.

302 E. L., Jones, *The European Miracle: Environments, Economies, and Geopolitics in the History of Europe and Asia*. 3rd ed. (Cambridge, UK; New York, NY: Cambridge University Press, 2003), 33.

303 Jones, *The European Miracle*, 41.

304 Jones, *The European* Miracle, 43.

building prevented catastrophes and thus provided a dependable space for urban capital investment. This was such an improvement, he believed, that it contributed to the "rise of Europe" in the early modern period.[305] Little evidence exists to support or reject such a claim of European building supremacy. Jones was correct, however, that stone building was driven by the risk of fire and continued lock-step with increased urbanization at the time of the economic rise of western Europe.

The materials that were used in each case were determined by the places where the urban material transformations occurred. Braudel discussed the timing and regional variation of the transition of European cities from timber building to the use of stone—both natural and anthropogenic. "Brick gradually replaced wood in buildings, from England to Poland, but it did not predominate immediately…London began to adopt brick in the Elizabethan period, at about the same time as Paris became a stone city…Similarly in Amsterdam, all the new buildings in the seventeenth century were made of brick," he wrote of the lithic building transformation.[306] These material transitions were directly related to regional building regimes. Quality building stones could be accessed in northern Italy and in the Paris Basin. British and Dutch cities, on the other hand, rested in the Thames Watershed and Rhine–Meuse–Scheldt Delta, bereft of such building materials. However, they could import stones. All regions had unique possibilities and challenges, but, as was likely true with the switch to coal in Elizabethan London, the choice was likely due to which materials were abundant over those that were scarce.

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305 Jones argues that durable structures and fire prevention were two keys to buildings being safe places from capital investment. Jones, 43.

306 Braudel, *Civilization and Capitalism*, 268.

For instance, although the lime industries of Paris persisted in the organic economy, manufactured building supplies were available. Like its counterpart across the channel, the city had ample raw materials for the production of mortar. In fact, a builder's dictionary published by T.N. Philomath in 1703 claimed the word "mortar" originates "from the French Mortier, a fort of plaster, commonly made of lime, and sand, and water, used by Masons and Bricklayers, in Building of Walls of stone and brick."[307] In the organic energy rich environments of the continent, building in Paris could maintain intensive use of brick and mortar even though each were produced with firewood. Although intensive amounts of wood fuel were used on the continent, there is no evidence of shortages during the early modern period in places like Paris. "In Paris alone, on the eve of Revolution, charcoal and firewood represented more than 2 million tons, that is 2 tons per head," Braudel estimated.[308] There was also little fear of running short on calcium carbonate as the entire Paris Basin is made up of large deposits.

The French city also had access to quality natural building stones. Braudel observed of this advantage when he wrote that, "there are innumerable sandstone, sand, rough limestone and gypsum quarries around Paris. The town cleared its own site in advance. Paris was built on enormous excavations."[309] The use of such stones persisted in the city well after the modern cement transition. Braudel continued, "rough limestone was widely quarried until the First World War, sawn up in the suburbs and transported

307 T. N. Philomath, *The City and County Purchaser and Builder's Dictionary* (London: Printed for John Nutt, 1703), 203.

308 Braudel, *Civilization and Capitalism*, 364.

309 Braudel, *Civilization and Capitalism*, 267.

across Paris by heavy horse drawn drays."[310] "We should not be misled:," the *Annales* school historian warned, "Paris was not always a stone city: to turn it into one was an immense labour, starting in the fifteenth century and requiring troops of carpenters from Normandy, roofers, makers of edge tools, masons from the Limousin, tapestry-makers specializing in fine-works and large armies of plasterers."[311]

The protestant countries were not as well endowed with quality building stones. Neither the population centers of Great Britain nor the alluvial land base of the Dutch Republic contained high quality stone quarries. Great Britain did contain such materials, but they existed far from the largest population centers. The monuments that drew the eye of Harrison and Leland in the sixteenth century were in the limestone rich regions in the middle of the island. Materials historian Martin S. Briggs described them as such, "the two chief regions where stone building was practiced were: (i) the limestone belt extending from Dorset coast to the Humber, through bath, the Cotswold, Northampshire, and Rutland, commonly called 'Cotswold' region; and (ii) the districts of west Yorkshire, north Derbyshire, north Lancashire, and so on, adjoining the Pennine Range." These quarries of quality limestone were far from the prosperous regions in the southeast of Great Britain that included the Thames Basin and East Anglia. Stones could be had from the Isle of Portland in the city from the Middle Ages. However, historian Harvey observed of southern Great Britain that, "prior to cutting stone in the isle of Portland,

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310 Braudel, *Civilization and Capitalism*, 268.

311 Braudel, *Civilization and Capitalism*, 268.

most large stone works could more easily import stones from northern France."[312] Dutch builders also had to rely on North Sea imports, notably from Norway.[313]

The British and Dutch, however, rested on alluvial sands that were fit for brick making. It is unknown exactly why these countries chose a divergent building material path, but the requirement of stone imports and brick making traditions likely each played a role. Builders in Great Britain and the Low Countries set out on a path of brick and mortar building from an early date. The Dutch were early leaders in this building trend. Davey noted that, Flemish and Dutch were leaders in brick production and use.[314] Their cities were also known by British contemporaries as being superior. For example, Balthazaar spoke of the wide streets and quality work in cities like Amsterdam in comparison to London by 1664.[315] Once that development path was set, builders preferred bricks over mortar. The case was reversed with stones. A sixteenth century account of stone use in the city noted that they "were sold very cheap, for all the buildings then made about the city were of brick and timber. At that time any man in the city might have a cart-load of hard stone for paving brought to his door for six-pence or seven-pence, with the carriage."[316] Some, like Indigo Jones imported stones to London

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312 Harvey, *Mediaeval*, 110.

313 Roberto Gargiani, *Concrete, from Archeology to Invention, 1700-1796: the Renaissance of Pozzolana and Roman Construction Techniques,* trans. Stephen Piccolo (London: Rutledge, 2013), 111.

314 Davey, *A History*, 80.

315 Balthazar Gerbier, *The First and Second Part of Counsel and Advice to All Builders: For the Choice of Their Surveyors, Clerks of Their Works, Bricklayers, Masons, Carpenters, and Other Workmen Therein Concerned. As Also in Respect of Their Works, Materials, and Rates Thereof. Written by Sr. Balthazar Gerbier, Knight* (London: printed by Tho. Mabb, for Tho. Heath at the Globe within Ludgate, 1664) 93.

316 Stowe, *Survey of London*, 80.

for monumental works like St. Paul's Cathedral. However, much of the city preferred brick over stone.

The major environmental difference between the North Sea countries included the source of limes. Contrary to the fossil endowment, the Dutch relied on substitutes for fuels and materials. In the late eighteenth century, the English chemist Casper Neumann observed that "the Dutch have no other lime for building than calcined sea-shells, particularly those of muscles."[317] When used in mortars, these proved a durable substitute. In Wren's *Parentilia*, an eighteenth century English treatise on building, the builder-author noted that "the vaulting of St. Paul's is a Rendering as hard as stone, it is composed of cockle-shell lime well beaten with sand."[318] Since chalk, found in abundance along the Thames was the primary source of mortars at the time of Wren's work, he must have thought more highly of seashell substitutes.

An added benefit of using shell limes involved them requiring less fuel to burn as was observed by Arthur Young in 1780.[319] By the mid-sixteenth century, densely populated areas in the swampy republic experienced firewood shortages but had alternatives. They dug peat as a biofuel substitute.[320] Historian John F. Richards observed that the Dutch use of peat helped ensure that, "energy intensive transforming industries—

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317 *The Chemical Works of Caspar Neumann, M.D., Abridged and Methodized With Large Additions, Containing the Later Discoveries and Improvements Made in Chemistry and the Arts Depending Thereon*, ed. William Lewis, M.B. and Fellow of the Royal Society (London: Printed for W. Johnston, G. Keith, A Linde, P. Davey, B. Law, T. Field, T Caslon, and E. Dilly, 1759), 540.

318 Sir Christopher Wren, *Parentalia or Memoirs of the Family of Wrens* (London: Published by Stephen Wren, 1750), 320.

319 Young, *A Tour,* 76.

320 John F. Richards, *The Unending Frontier: An Environmental History of the Early Modern World* (Berkeley: University of California Press, 2005), 54.

distilling, beer making, lime boiling, brick and tile making, salt boiling, and iron working—all grew rapidly after the revolt."[321] Historian Rolf Sierfele described that "there were natural barriers to supplying London with firewood by the Thames, while the town of Rotterdam could be supplied by the Rhine with wood from the Black Forest…For this reason, it was apparently more effective to ship coal from the region around New Castle to London than to carry wood, even though it was far closer in the Weald of Sussex or a similar large forest."[322] British industries needed coal imports whereas the Dutch could maintain their building regime with substitutes. Although they had similar building regimes, there was a strict division between the mortar production processes between the two countries. The Dutch relied largely on burning seashells with peat or imported coal whereas the British almost exclusively burned chalk with coal.

Access to building timbers could also be had with continental rivers in ways that the British could not. Related to the firewood scarcity debate, the question of whether or not there were shortages of building timbers in pre-industrial Great Britain persists. One of the most balanced accounts of building material availability is provided in naval historian Robert Albion's *Forests and Sea Power.* Albion described the shortages of quality building timber as related to the preference of the British Navy for oak and destruction of woods due to bad policy and political strife. The British Navy placed high value on native timber, which consequently removed much from the building market.[323] Land use also favored agriculture over building. Since, in most cases, building timber

321 Richards, *The Unending*, 54.

322 Rolf Peter Sieferle, *The Subterranean Forest: Energy Systems and the Industrial Revolution* (Cambridge: The White Horse Press, 2001), 81.

323 Albion, *Forests and Sea Power*, 126-127.

was grown on the same land as firewood, they competed for space.[324] Since the firewood was cut at around 20 year intervals and the building timbers took as long as 150 years, there was a greater incentive to dedicate land to agriculture with regular returns.[325] Although there was no clear instance of a lack of building timbers, Albion recorded building timber shortages beginning around King Henry VII's reign and continuing through the Civil War. "When Thomas Cromwell began the attack on the monasteries in 1535, England had scarcely a thought of the future scarcity of timber," Albion explained.[326] "When Richard Cromwell abdicated, a century and a quarter later, the splendid heritage of oak had been wasted," he concluded. This posed a challenge for builders at the time as the timbers that remained were often reserved for the British Navy.

As has been stressed throughout this study, brick building did not occur without related timber building materials. For instance, the building codes that followed the fire mandated the use of oak timbers to support masonry works. This was only possible at the time due to imports. After the Great Fire of 1666, the architect in charge of much of rebuilding the city, William Wren, lamented that "our sea-service for Oak, and the Wars in the North-Sea, make Timber at present of Excessive Price. I suppose 'ere long we must have recourse to the *West-Indies,* where the most excellent Timber may be had."[327] He relied on imports to meet "the mighty Demand for the hasty Works of thousands of

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324 Albion, *Forests and Sea Power*, 99.

325 Albion, *Forests and Sea Power*, 118.

326 Albion, *Forests and Sea Power*, 130.

327 Christopher Wren, *Parantelia or Memoirs of the Family of Wrens* (London: Printed for T. Osborn, 1701), 320.

houses at once, after the Fire of *London*."[328] Although the costs of timber remained high, its persistent use as a building material demonstrated that timber was not impossible to secure. Albion records the increased imports from Norway and the Baltic due to lack of domestic timbers. He noted that, over time, "the imported timber came more and more to replace oak."[329]

It is in this environment and cultural building tradition that the fossil city took shape. Wren gained the mandate "to rebuild London."[330] This was a bit of hyperbole contained in the Wren's *Parentelia*, but he was responsible for much of the larger building projects after the fire. "After the most dreadful Conflagration of London, in the fatal year 1666. Dr. Christopher Wren was appointed Surveyor-General and Principal Architect for rebuilding the Whole city; the Cathedral Church of St. Paul; all the parochial Churches (in Number Fifty-one, enacted by Parliament, in lieu of those that were burnt and demolished) and other publick Structures," the account of his works noted.[331] Due to his central role in rebuilding so many structures, Wren's discussions were telling of the material circumstances of the transformation of the city. He described "the manner of building the City of London, practiced in all former Ages, was commonly with timber, a material easily procured, and at little expense, when the Country was overburdened with Woods." He continued, "this mode continued until the two fatal Years 1665 and 6; but then the successive Calamities of Plague and Fire, gave all People

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328 Wren, 308.

329 Albion, *Forests and Sea Power*, 157.

330 Wren, *Parentilia*, 261.

331 Wren, *Parentilia*, 263.

Occasion seriously to reflect on the Causes of the Increase of Both to that excessive Height; viz. Closeness of Buildings, and Combustible Materials, and hence the Wishes for the necessary Amendment of both, by widening the Streets, and building with Stone and Brick, became universal."[332] Wren was half correct. Wide streets were valued to prevent fire and increase airflow. However, Wren was unable to accomplish this goal due "to the unique property rights of London."[333]

Even though the form of the city did not change much after The Great Fire of 1666, its material transition was pronounced. The fire provided a blank slate and a reason to rebuild with fire-resistant materials. The reconstruction of London with brick and mortar was outlined by parliamentary law, but the dominant building material in the city was determined long before. The fossil endowment allowed for the production of brick and mortar outside of the organic economy. Stones would have afforded similar qualities, but quarries of high quality stones did not exist in the Thames Basin or the Low Countries. Where they did, as in Paris, the urban architectural path took a different direction. Not perceived at the time, those who built in cities with brick and mortar outside of the organic economy had set out on the path that urban building still takes today. At each stage of building, and rebuilding, there were stone and timber alternatives available in London. Only those made in the fossil economy could avoid pressures on surrounding landscapes, provide abundant supply and also fire-resistant qualities. By the eighteenth century, this made London firmly a brick and mortar city.

Building From The Stock

332 Wren, *Parentilia*, 263.

333 Wren, *Parentilia*, 265.

The brick and mortar building regime remained dominant in London well after the seventeenth century. Although this afforded a building material matrix outside of the organic economy, it still had costs. John Evelyn's 1670 pamphlet, *Sylva*, provides an example of the tension between the advantages and disadvantages of London's early modern building tradition. Although it encourage tree planting in an attempt to reforest areas for use by the British Navy, Evelyn still complained of the air pollution from urban industries that used coal. He advocated "for the further purgation of this august metropolis [London], had they there, (or did they yet) banish and proscribe those hellish vulcanos, disgorging from the brew-houses, sope and salt-boilers, chandlers, hat-makers, glass-houses, forges, lime-kilns, and other trades, using such quantities of sea-coals, one of whose funnels vomits more smoak than all the culinary and chamber-fires of a whole parish."[334] He did not perceive the relationship between the availability of timber and mineral industries. The 'hellish volcanoes' freed up land for dedicating to timber and in fact supported the overall aim of the pamphlet. Like those who sought to regulate the lime industries of the city centuries before, demand for abundant building materials produced outside of the organic economy proved valuable enough to overcome such challenges.

Issue besides air pollution persisted as well. Wren observed the low quality of the bricks of London shortly after the fire. He wrote that, "good bricks are not now to be had, without greater Prices than formerly, and indeed, if rightly made, will deserve them, but Brick-makers spoil the earth in the mixing and hasty burning, till the Bricks will hardly bear Weight, though the earth about London, rightly managed, will yield as good Brick as

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334 Evelyn, *Sylva*, 278.

were the *Roman* bricks."[335] This issue persisted throughout the next few centuries as historian Dorothy George described that "the collapse of new or half-built houses is frequently commented on in eighteenth century newspapers."[336] She profiled an article from the *London Chronicle* from 1764 to demonstrate such circumstances:

> He will tremble for those who are to inhabit the many piles of new buildings that are daily rising in this metropolis. When we consider the practice among some of the brickmakers about this town, we shall not wonder at the consequence, though we must shudder at the evil. The increase of building has increased demand and consequently the price of bricks. The demand for bricks has raised the price of brick earth so greatly that the makers are tempted to mix the slop of the streets, ashes, scavenger's dirt and everything that will make the brick earth or clay go as far as possible.[337]

The brick manufactories were not very efficient either. Like the lime kilns, brick makers required coal fuel. Thus, a steady fuel supply was central to maintaining the urban industry. A point of the importance of coal to these industries came shortly before the fire. "As early as 1640, a shortage of coal engendered a serious crisis in the building trades of the capital," wrote Nef, "various owners of limekilns, having been refused supplies by the coal merchants, petitioned the Privy Council that they were 'bound by covenant to serve…with lime…all the bricklayers and others…who are now building for persons of quality; which they cannot performe unlesse they may have coale to keepe in their fryers, soe that of necessity the said Buildings must suffer.'"[338] These industries, along with brick factories then were seen by their operators as not only essential, but also dependent on a reliable and continuous supply of coal.

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335 Wren, *Parentilia*, 319.

336 Dorothy M. George, *London Life in the 18th Century* (New York: Capricorn Books, 1965), 83.

337 Quote reproduced in George, *London Life*, 84.

338 Nef, *The Rise*, 205.

Brick manufacturing follows essentially the same trajectory. Gerbier also noted in 1664 that the "kiln, which will consume for the making of twenty thousand of bricks, fifteen load of Wood, at ten shillings the load; of bricks burnt in a clam (being burnt with sea coals) there are at the least in twenty thousand, five thousand unfit for work."[339] There was a trade-off of using the abundant sea coles. The problem included what John Rovenson wrote in his *Treatise on Metallica* published in 1613, coal 'doth many times spoil much of the brick-clamp by making it run together in a lump.'"[340] Therefore, the use of coal for brick making was one of the only options for the British, but it was not the best one. As historian Nef put it, "yet in London so high was the price of wood and so great the demand for bricks, that despite its failings, it was common to fire them in Newcastle coal."[341] The mineral building regime clearly maintained advantages not held by other materials.

There was similar confusion about the persistence of the manufacturing of mortars with coal. The British architect Balthazar Gerbier, was confused by the use of coal in kilns. He understood the lack of timber, but not the value of coal. He wrote in 1674:

> But if there were such a quantity of Wood [in England] as in the *Indies,* there could be more lime burnt in twenty four hours, then otherwayes in a moneth: The burning of lime in *China* and other parts of the *Indies,* being as followeth, *viz.* They make a round pile of great wood, leaving a cross hollow way through it from the bottom almost to the top, which is raised to a height according to the Circle, there is proportionably so much Stone heaved thereon as it will hold, the fire is put in the Centre, and in the

339 Gerbier, *Counsel and Advice*, 52-53.

340 Quote reproduced in Nef, *The Rise,* 217.

341 Nef, *The Rise,* 254.

> middle of every cross way, and as it burns makes an Overture at the top, and the stone burning by degrees falls still in the middle of the pile, and of the Walks, which at last is covered with the Cinders of the burnt wood, and proves a most strong well burnt Lime.[342]

The production of cement was limited by the size of the kiln because the sustained production of cement with coal required pacing the production. If all the lime was produced at once, much would have been wasted. To Gerbier, this was a great hinderance. Apparently unbeknownst to the seventeenth century builder, fossil cement afforded long term over short term advantages by avoiding the limits of the organic economy.

There was significant confusion about the building regime in London. Why would it persist in the way that it did if other methods could provide similar yields, less exposure to air pollutants and better building? Many sought to identify the cause of the low quality and propose a remedy. The most authoritative examination of the mineral mortars of eighteenth century London was taken up by Dr. Bryan Higgins who examined multiple assumptions regarding the causes of the mortar's low quality—raw material, firing technology and transportation. He first set out to determine the quality of the mortars in the 1770s. "As the strength and duration of our most useful and expensive buildings depend chiefly on the goodness of the cement with which they are constructed, I looked to the improvement of mortar as a subject of great importance, in this country particularly, where the weather is so variable and trying, and the mortar commonly used is so bad, that the timbers of houses last longer than the walls, unless the mouldering

342 Gerbier, *Counsel and Advice to all Builders*, 57.

cement be frequently replaced by pointing."[343] Dr. Higgins may have been hyperbolic in his claims of bond timbers outlasting the structures, but his tests on mortars diagnosed a particular problem with the mortars. His next aim was to prescribe a solution.

To do so, he carried out a number of tests. He began with the question of materials and their production. Dr. Higgins observed that, "I was satisfied that the lime which is most compleatly burned is the best for mortar. Considering the heat, which I found…necessary to extricate the last portions of acidulous gas from chalk or limestone, to be much greater than what is ever excited in making lime in this country or elsewhere, so far as I had observed or could learn from others; I suspected that the lime commonly used in building is seldom or never sufficiently burned."[344] Through these tests on firing, he discovered that it was not chalk which was lower quality. The inquisitive builder continued, "these remarks are applicable to mortar made with stone-lime; though the stone-lime be generally better than the chalk-lime used in London, because they are obliged to burn it better, as it will not slake otherwise."[345] He ended with the observation that, "I was convinced that the only impediment to their slacking consisted in their not being sufficiently burnt in the kiln."[346] Through his own controlled experiments, he uncovered that the insufficient burning of lime was the cause of the failures in the city..

His next hypothesis was related to the time between production and use. A second point that Dr. Higgins stressed was the detrimental nature of the atmosphere to finished

343 Bryan Higgins, *Experiments and Observations Made with the View of Improving the Art of Composing and Applying Calcareous Cements, and of Preparing Quick-Lime* (London: printed for T. Cadell, 1780), 2.

344 Higgins, *Experiments*, 22.

345 Higgins, *Experiments*, 27.

346 Higgins, *Experiments*, 28.

lime. He noted that, “the workmen usually slake the lime mixed with the sand or gravel in great heaps, and do not skreen it until the most useful part is debated by that which flakes after five or six hours or more, and which is little better than so much powder of chalk. But if they would skreen the lime in about half an hour after the water is thrown on it, the mortar would be much better, although the quantity of lime in it should be much less.” Overall, he observed that, “lime grows the more unfit for mortar every hour that it is kept exposed to air, whether in a heap, or in casks pervious to air.”[347] This was a fatal flaw as Higgins saw it. It also demonstrated his misunderstanding of the value of quantity. Slaking the lime over a longer period of time provided more lime of lower quality, which apparently was preferred by the lime-burners and masons of London.

There is little information on what the workmen knew of this process, but carrying out this project daily must have provided them a deep understanding of the costs associated with different production sites and set a particular path. Dr. Higgins dismissed this earned knowledge outright. He described their process as wasteful as the lime “grows worse for mortar every day that it is kept in the usual manner in heaps or in crazy casks; that the workmen are mistaken in thinking that it is sufficient to keep it dry; that lime may be greatly debased without slaking sensibly; and that the superficial parts, of any parcel of lime, which fall into small fragments or powder without being wetted, and merely by exposure to air, are quite unfit for mortar; since this does not happen until they have imbibed a great deal of acidulous gas . . - I now saw more clearly another cause of the imperfection of our common cements.”[348] This problem seemed to be particularly

347 Higgins, *Experiments*, 33.

348 Higgins, *Experiments*, 35.

acute in the city, "In London particularly they use lime which is burned, at the distance of ten or twenty miles or more, in Kent and elsewhere, with an insufficient quantity of fuel. This lime remains in the kiln, to which the air has access, for many hours after it is burned."[349]

This point deserves attention because there is a clear trade-off between solving the issue of air pollution persistent in the city from the lime kilns for roughly 500 years and the quality of lime. By the eighteenth century, Evelyn's suggestion that it "be worth a severe and publick edict, to remove these vulcanos and infernal houses of smoak to competent distance; some down the river, others (which require conveniency of fresh-water) up the Thames, among the streams about Wandsworth, &c? Their commodities and manufactures brought up to capacious wharfs, on the bank, or London side, to the increase of a thousand water-men and other labourers, of which we cannot have too many?"[350] Daniel DeFoe described such a location of industries in his tract from the mid-eighteenth century, "there is little remarkable upon the river, till we come to Gravesend, the whole shore being low, and spread with marshes and unhealthy Grounds, except with small intervals, where the Land bends inward as at Erith, Greenhith, North-fleet, &c. in which Places the Chalk Hills come close to the River, and from thence the city of London, the adjacent Counties, and, even Holland and Flanders, are supply'd with Lime for their building, or Chalk to make Lime, and for other uses."[351] Hatcher supported this

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349 Higgins, *Experiments*, 36.

350 John Evelyn, *Sylva: Or a Discourse of Forest, Trees & The Propagation of Timber*, vol. 1 (London: Arthur Doubleday & Company), 278.

351 Daniel Defoe, *A tour thro' the whole island of Great Britain, divided into circuits or journies* (London: JM Dent and Co, 1927), 10.

observation, noting that by the eighteenth century, “the inexhaustible demands [for lime] of South London in the seventeenth century were supplied in large part by clusterings of great kilns around Gravesend and Northfleet on the Thames estuary.”[352] This seems not to have been an insurmountable threat to the quality of lime as Dr. Higgins described a solution as “a cask of chalk lime is not to be opened until the moment when the workman is ready to slake the lime; and the greatest expedition is to be used in the slaking, in making the mortar, and in applying it to use.”[353] This was the final significant suggestion provided by Dr. Higgins.

In all of Dr. Higgins’ observations, there was a solution that could raise the quality of London’s mortars to a suitable standard. By particular firing, storage and transportation methods, the persistent problems of low quality building would be remedied. He concluded that “in these comparisons I could not perceive that chalk lime, judiciously prepared and used, was in any respect inferior to the best stone lime…therefore the chalk - lime chemically or technically tried, appears to be equal, if not superior to stone lime, in its cementing powers, when it is properly used.”[354] As exhaustive as Higgin’s studies were, his suggestions were never adopted by lime burners or builders. The benefit of fossil building was that it could be carried out without the limits of the organic economy and thus in great quantities. The method, although not the best structurally, allowed for the production of abundant amounts of fire-resistant materials to feed the seemingly insatiable demand of the growing city.

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352 Hatcher, *The History,* 430.

353 Higgins, *Experiments*, 212.

354 Higgins, *Experiments*, 207-208.

That benefit can be seen in the divergence between London, and Great Britain in general, from their counterparts in the Low Countries. The British and Dutch had similar material, political and cultural connections that persisted throughout much of the early modern period. The British and the Dutch shared a common material heritage as well. They each also had extensive colonial holdings and associated wealth by the mid-eighteenth century. They each also departed considerably from their Mediterranean counterparts. Economically, England and the Netherlands tracked closely with each other and away from the rest of the world.[355] Economic analyst, Robert Allen observed of this early divergence, "the economic expansions of the Netherlands and England during the early modern period were important achievements, for they marked a departure from the Malthusian past. For the first time in western history, the economy kept pace with the population."[356]

Nevertheless, Great Britain pulled ahead in the struggle against the environment through exploiting their unique fossil endowment. As mentioned above, the English thermal industries did not put the same pressures on the environment as thermal industries that used firewood, an organic fuel supply. The Dutch could use peat to the same effect. Richards noted that "peat and coal formed a low-cost energy supply that made possible an extraordinary level of comfort for the Dutch at home and an equally unusual concentration of energy-intensive industry."[357] Therefore, the energy trap that

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355 Robert C. Allen provides a compelling analysis of laborers wages and prices of good to demonstrate this divergence. See: Robert C. Allen, "The Great Divergence in European Wages and Prices from the Middle Ages to the First World War." *Explorations in Economic History* 38, no. 4 (2001): 411-47.

356 Allen, "The Great Divergence," 434-435.

357 Richards, *The Unending*, 55.

likely contributed to the fall of the Roman concrete building regime due to a reliance on wood fuel, did not occur in the North Sea. However, the reliance on outside sources for coal was a significant factor in industry. Richards continued to discuss the impact of this on industry. "Dutch industries, not homes, were the primary users of coal," the environmental historian observed.[358] England supplied that coal through the North Sea trade networks. These trading networks offered a windfall for when peat became increasingly exhausted and peat prices increased.

Beginning in the late seventeenth century, coal began to supplement peat in heating as well and constituted around 2/5ths of the total Dutch energy supply. As peat production declined in the following century, more coal was increased until the two sources reached parity.[359] Unlike with the sources of peat in the Netherlands, England had the cheap coal necessary to sustain thermal industries seemingly indefinitely. These supplies became dear when disruptions in trade like the continental system or declining options for energy substitution put pressures on domestic manufactures. Historian John U. Nef described the importance of this for thermal industries. He stated that "the advantages which Great Britain possessed in abundant supplies of cheap coal began to tell in many industries, in which fuel was one of the chief costs of production, particularly in glass, salt, brick, and lime-making."[360]

Just as coal allowed for the British industries to avoid limits to fuel supply, so too did the calcium carbonate deposits of the island. Dr. Higgins proved that, if need be, the

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358 Richards, *The Unending*, 55.

359 Richards, *The Unending*, 55.

360 Nef, *The Rise*, 324.

materials could have been improved. The need never came. Haphazardly burning massive amounts of chalk with low grade coal to create seemingly endless supplies of mortar was a process unique to British cities. It is questionable if the rebuilding of London and its rapid growth could have been maintained without it. Although not understood at the time, this was a clear distinction between the building regimes of Great Britain and the continent during this transformative period in European history. The British were the only early modern peoples that could build in dense urban areas outside of the organic economy.

Unfortunately, there is no definitive evidence to measure the volume of the fossil cement industries of London. However, there is ample information for brick manufacturing and use. Historians DeVries and Woude described one account written "in 1804 of the brickworks located along the Holland Ijssel river. There, production was said to have fallen from 126 million in 1672 to 43 million in 1700. The number of brick kilns fell, according to this account, from 45 in 1672 to 31 in 1700, and further to 20 in 1802."[361] Although this is one specific example, the Dutch historians estimated that this was typical in the Dutch Republic and reflected an "overall trend [that] must have been downward."[362] The British, on the other hand, had an upward trend in brick making and use.[363] Shannon's Brick Index demonstrates, "a very rapid rate of growth in bricks and, inferentially, in building from 1785 to 1793,…from 1793, it shows a sharp fall to 1799—

361 DeVries and Woude, *The First*, 305.

362 DeVries and Woude, *The First*, 305.

363 H. Shannon, "Bricks: A Trade Index, 1785-1849." *Economica*, no. 3 (1934), 300-318.

six years of bad…then it rises with almost equal sharpness to 1803."[364] After a short slump, brick and mortar building grew again. As Shannon suggests, there are many reasons for the rise and fall of the brick building regimes, but it is clear that brick, and hence lime based mortar, production was on the rise at the same time that the Dutch experienced a steep decline.

Few considered the brick and mortar industries that served London as advanced technology during the early modern period. The low quality of brick and mortar building in the British capital was well known. However, the continued use of such inferior building materials demonstrated a feature of the building regime that has since grown to megalithic proportions. London was the only large capital city that could produce massive amounts of building materials, rapidly and with little environmental impact. As the city grew dramatically in the eighteenth century so too did the building. At no point was the supply of materials interrupted in an age of mercantile trade and persistent war. By the end of the eighteenth century, Dr. Higgins had explained the method for creating dependable cements. His suggestions would have slowed the production and were rejected by the city's lime burners. What Higgins did not perceive was the value of being able to produce materials rapidly to feed an insatiable demand from the city that had, by then achieved global imperial supremacy. London was the only city that could sustain a move away from organic building through the use of brick and mortar made in the mineral economy. It has largely remained unnoticed, but this is a significant moment in human history that provided a demonstrated the benefits that could be drawn from building from the stock.

364 Shannon, "Bricks," 301.

Conclusion:

The grand facades of cut stone and plaster in Paris continue to hold the eye of art historians fawning over the city's Baroque and Rococo architecture. As awe-inspiring as early modern Parisian buildings may have been, the natural stone monuments were examples of development in the wrong direction. It was the stout, cold and drab buildings of London that proved the template for modern urban building. In fact, the ability to overcome environmental limits proved essential to the urban growth of the city. British urbanization in the two centuries leading up to the Industrial Revolution was a complex process related to agriculture and urban building. By leveraging their fossil advantage, the British avoided the trade-offs associated with development in the organic economy. The lime kilns of London were the earliest example of fossil fuel dependency, with associated air pollution. They also afforded a building material that did not require land be set aside for firewood or timber. Furthermore, liming the soil afforded agricultural surpluses in an unlikely climate. Rebuilding the city with fire-resistant materials after the Great Fire of 1666 was also possible in large part due to the abundant mineral materials that—unlike the timber supplies—could be sustainable produced and used without the interruptions associated with imported materials. Nevertheless, building in the city remained subpar. The regular collapse of buildings caused many to question the low quality materials used in the British capital. Yet, the methods and materials continued to be used. To the scientifically minded like Dr. Bryan Higgins, there was a solution that could be had. To the lime-burners and masons of London, changing their method would have slowed production. Their success speaks for itself as the amount of brick building increased dramatically in the city at the end of the eighteenth century while continuing to avoid environmental limits. This was the first instance of building from the stock, which has since greatly altered the built environment around the world.

CHAPTER FOUR

WATER

Introduction

British engineer John Smeaton is perhaps the most well-known figure in the history of construction. He was born to build. His daughter, Mary Dixon, reflected on this innate propensity in a eulogy attached to the introduction to Smeaton's *Reports,* published in 1812. "I say, 'six years old to sixty,'" Mary wrote, "because while in petticoats, he was continually dividing circles and squares; all his play-things were models of machines, which destroyed the fish in the ponds, by raising water out of one into another."[365] Hydraulic construction had occupied his mind from a young age. This preoccupation drew him to the Eddystone Rocks in 1755, a site of repeated disasters. Many ships were destroyed on their approach to the English Channel after running into the protruding reef hidden just beneath the waves at high tide. Smeaton was tasked with constructing a lighthouse on these slippery stones where others had failed due to the difficulties of building below the high water line. The young engineer succeeded and Smeaton's Tower stood until 1877, only to be relocated because of the deterioration of the rocks it was built on.[366] This longevity was owed to Smeaton's own "water cements." He developed this original concoction by substituting calcium carbonate with a high clay content for pure limestone, which strengthened the material. Pozzolan sands were also used by the builder to create his waterproof cement. Smeaton's mixture provided a

365 Mary Dixon, "The Committee of Civil Engineers, Fellfoot, near Kendal, 30th October, 1797," in *Reports of the late John Smeaton. F. R. S., made on various occasions, in the course of his employment as a civil engineer*, by John Smeaton (London: Printed for Longman, Hurst, Rees, Orme, and Brown, Paternoster-Row, 1812), xxvi.

366 J.N. Douglass, "Note on the Eddystone Lighthouse," in *Minutes of the Proceedings of Civil Engineers*, vol. 53, 1877-78, 247.

durable hydraulic bonding agent that was used in the decades after his discovery to build the metropole of the British Empire and the foundation of the Industrial Revolution.

Smeaton's Tower was revered by builders for centuries as a symbol of British ingenuity. It earned him the posthumous title of "the father of Civil Engineering." His water cements were known to builders across the island and throughout the building regimes of the West. Writing in 1838, Major-General Sir Charles William Pasley noted that, "Smeaton overset the prejudices of more than two thousand years, adopted by all former writers, from Vitruvius in ancient Rome to Bélidor in France and Semple in this country, who agreed in maintaining that the superiority of lime consisted in the hardness and whiteness of the stone."[367] The excitement may have been overblown. His material was still a pozzolan cement. Vitruvius and Bélidor would have recognized it. Even the use of impure calcium carbonate was not simply the result of individual genius. Smeaton was able to experiment with various calcium carbonate deposits due to the abundance of lime industries that, by the eighteenth century, existed across Great Britain. Nevertheless, the material did prove a breakthrough for hydraulic construction on the island.

There was a difference between the "hydraulic architect" represented by Belidór and the British "civil engineers" that emerged after Smeaton. Prior to Smeaton, the planners and managers of large-scale hydraulic projects were often brought in from the continent.[368] After Smeaton, an array of British builders gained prominence and oversaw

367 Charles Pasley, *Observations on Limes, Calcareous Cement, Mortars, Etc*. (London: J. Weale, 1838), 40.

368 Samuel Smiles, *Lives of the Engineers: Early Engineering* (London: John Murray, 1904), vi-v.

continental projects.[369] This was not the only mid-century shift in Great Britain's fortunes during the second half of the eighteenth century. British imperial consolidation was achieved after the Seven Years' War and shortly after, which left few competitors to British Naval supremacy. The increase in steam production followed 1760 and grew rapidly into the nineteenth century.[370] Iron production in Great Britain increased in tandem.[371] Many historians have sought to explain the factors that drove this transformative period in British history. Individual genius, cultural factors and technological innovation have all been posited as causes. None address the role of hydraulic building on the island after Smeaton's experiments of the 1750s.

One way to consider the role of cement in this process is to consider the causal factors of British economic and industrial take-off during the early nineteenth century. Many historians have proposed reasons for the British 'great divergence' that began in the late eighteenth century and was complete by the middle of the next. Kenneth Pomeranz' thesis that colonies and coal were responsible for British economic take-off has reached a paradigmatic position in such scholarly debates.[372] This chapter adds cement as a third "c" to this insightful explanation of the drivers of the British great divergence. It is true that resources pillaged from the colonies and the mineral economy of Great Britain formed a fateful convergence in world history somewhere around the

369 For instance, Telford was used for the construction of the Gotha Canal in Sweden. *Encyclopaedia Metropolitana*, vol. 23, eds. Edward Smedley, Rev. Hugh James Rose and Henry John Rose (London: B. Fellows and J. Rivington, 1845), 201.

370 Von Tunzelmann, *Steam Power and British Industrialization to 1860* (Oxford: Clarendon Press, 1978).

371 Sierfele, *The Subterranean*, 115.

372 P.H.H. Vries, "Are Coal and Colonies Really Crucial? Kenneth Pomeranz and the Great Divergence," *Journal of World History* 12, no. 2 (2001): 407–446.

turn of the nineteenth century.[373] They each relied on hydraulic infrastructure in the form of ports and canals. Following Smeaton's discovery of the durable and waterproof qualities of the impure lime deposits in Great Britain, such technology grew dramatically.

The availability of significant quantities of materials for building in water alone does not explain this phenomenon. A central argument of this dissertation is that cultural as well as material factors drive large-scale building projects. For instance, the Eddystone Lighthouse was funded to assist ships returning from colonial ventures that entered the English Channel and then turned north to the Port of London or vice versa. Smeaton's discovery of "water cements" was driven by the emphasis on hydraulic construction by the British maritime empire. In the roughly 80 years following Smeaton's discovery, the material was also used to transform the Port of London through its use in docks, seawalls and bridges. All served a specific purpose, to provide secure and rapid transportation of colonial spoils from the British Empire.

Smeaton's career spanned most of the second half of the eighteenth century, the moment when British global imperial expansion solidified. He witnessed investments in hydraulic building for the colonial project that included seawalls, docks and piers. The most significant application of his material to such colonial infrastructure included the reconstruction of the Port of London. Between 1800 and 1831, the Port of London along the Thames River was transformed from a series of wooden wharves and mud landings into a network of docks, wharves and bridges that expedited the import of goods to London and the export of vessels throughout the empire. The new infrastructure was built with mixtures similar to those pioneered by Smeaton. Although not the sole reason for

373 Pomeranz, *Great Divergence*.

such building projects, improvements in the materials for building under water greatly increased the ability of British imperialists to move goods rapidly and securely through the metropole of the British Empire.

Domestically, coal was an essential ingredient of the industrial development that tracked closely with the consolidation of the global British imperial project. The use of fossil fuels in iron production and for steam power have been the focus of many historical accounts of British industrialization.[374] Many others have considered the role of transportation in facilitating the movement of coal to sites of industrial production.[375] The period following the 1760s has been described as the "Canal Age" where a series of canals were constructed for such ends.[376] Increasingly over time, the combination of lime made from impure calcium carbonate and pozzolan sands formed a mixture for the aqueducts, locks, bridges and other essential features of artificial waterways that by 1800 crisscrossed the island. This web of canals connected the industrial towns to the agricultural and building goods of the hinterlands. They tied them to coal pits and stone quarries as well. All of which were essential goods and materials for British industrialization.

This chapter posits that British imperial consolidation and industrialization were greatly aided by hydraulic cement similar to the mixtures discovered by Smeaton. A recurring theme of this study is that raw materials and fuel as well as robust building regimes and demand for large-scale building on land and under water are necessary for

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374 For an examination of each process and their relation to the Industrial Revolution, see: Landes, *Unbound Prometheus*.

375 Beaumont, *Treatise on the Coal Trade*, 2.

376 Hadfield, *Canal Age*.

such intensive building with anthropogenic stones. Great Britain from the mid-eighteenth century forward was a location where these material and cultural drivers of monumental lithic building converged. The use of Smeaton's cement mixtures in building the infrastructure of the Port of London created state of the art infrastructure for a metropole whose reach extended around the world. Canals made with hydraulic cements moved goods, materials and fuels to centers of intensive production in a process that helped create the conditions for industrialization. The foundation for the British great divergence was built with cement.

Hydraulic Architecture

As was demonstrated in the first chapter, little had changed regarding the Roman cement mixtures used across western Europe when Belidór published *Hydraulic Architeque* in 1753. The Westminster Bridge, begun in 1839, was an example of the state of hydraulic building in Europe at this time. A French Engineer named Lebeyle was brought in to build the project. He utilized methods that included using coffer-dams to divert the river and set foundations. Lime was mixed with Dutch *trass* for the cement on the project.[377] It was the end of an era. Shortly after the bridge was completed, British hydraulic building expanded dramatically. No longer were continental builders relied upon as British engineers studied continental methods and employed cement mixtures similar to those discovered by Smeaton. Before exploring the material breakthrough that facilitated this expansion of British hydraulic building, it is useful to consider the broader cultural and material context of the western European building regime in the final half of the eighteenth century.

377 Smeaton, *Narrative*, 100.

The revolution in British hydraulic construction played out in an atmosphere of increasing imperial consolidation. "In 1615 the British Isles had been an economically, politically fractious and strategically second class entity," wrote British imperial historian Niall Ferguson. "Two hundred years later Great Britain had acquired the largest empire the world had ever seen, encompassing forty-three colonies in five continents."[378] This imperial growth was related to the mechanism of the joint stock companies who sought to expand their wealth through imperial conquest. Some of the earliest were the English and Dutch East India companies formed in 1600 and 1602, respectively. Global material flows were also greatly expanded by such joint stock companies that had grown considerably by the eighteenth century. The British Navy was also influential in securing the country's global imperial position by the conclusion of the Seven Years War. Even earlier, it had gained unfettered access to Mediterranean trade goods.[379] Each were additions to the long extant North Sea trade that reached back centuries. Due largely to this maritime hegemony, Smeaton had access to materials that his predecessors did not. For instance, pozzolans were available to Smeaton due to being discarded in 1753 by the builders of Westminster Bridge.

British imperial growth was connected to the centuries-old process of European imperial expansion. The growth of European port cities from the sixteenth century forward demonstrated the gains that were had from this emergent world trade system.[380]

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378 Niall Ferguson, *Empire the Rise and Demise of the British World Order and the Lessons for Global Power* (New York: Basic, 2003), 43.

379 Roberto Gargiani, *Concrete, from Archeology to Invention, 1700-1796: the Renaissance of Pozzolana and Roman Construction Techniques,* trans. Stephen Piccolo (London: Rutledge, 2013), 111.

380 Immanuel Maurice Wallerstein, *The Modern World-System* (Berkeley: University of California Press, 2011).

There is a direct connection between colonial exploits and the European economic growth displayed in such urban areas. De Vries suggests that "from Hamburg to Cadiz, the major ports – including Liverpool, Bristol, and Cork in the British Isles – grew by 250 percent between 1600 and 1750."[381] One could also add London to the list of cities that grew from the spoils of colonial trade. The British metropole emerged as the largest and most developed of these European port cities by the end of the eighteenth century. Wrigley observed that "relative to her neighbors and rivals, …England in the seventeenth and eighteenth centuries was making rapid economic progress."[382] The rise of port cities demonstrated the growth of a world system that sought to direct goods and materials to European urban centers.

Hydraulic building in European port cities was funded by profits from colonial trade, but the metropolitan exchange of materials and ideas shaped its possibilities. Ideas also passed through such metropolitan areas. Hydraulic building techniques were drawn from the texts of continental architects in the service of European states that included Vitruvius, Alberti, Scamozzi, Belidór and others. Prior to Smeaton's discovery, the continental builders were renowned as the leading builders of western Europe. After Smeaton, British builders internalized this knowledge and replaced their continental counterparts as the ascendant builders of western Europe.

There was also a material feature to the British divergence in hydraulic building, which can be outlined by comparing the island-nation to its closest neighbors, The Dutch

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381 Jan De Vries, *European Urbanization, 1500-1800* (Cambridge, Mass: Harvard University Press, 1984), 152.

382 E.A. Wrigley, *Continuity, Chance and Change: the Character of the Industrial Revolution in England* (Cambridge: Cambridge University Press, 1980), 16.

Republic and France. By the turn of the nineteenth century, multiple geo-political issues reoriented the balance of power in the North Sea to England's favor. For example, there were a number of specific events that ended the prosperity of the Dutch Republic. The Fourth Anglo-Dutch War, won by the English, left the VOC cut off from colonial lands by 1784. This severed the largest profits of the lucrative trade that had persisted for centuries. These were transferred instead to the English whose own East India Company filled the colonial void left by the Dutch in the Indian Ocean. On land, shortly after the formation of the French Republic in 1794, the Netherlands were occupied, thereby restricting domestic profits as well. Beyond military indemnities, the Dutch oceanic trade was further ground to a halt through Napoleon's Continental System. Dutch historians DeVries and Woude observed that "the ability of these external forces to wreak havoc upon the economy was powerfully enhanced by the old Republic's own accumulated and unattended weaknesses. The Republic could protect neither its merchant ships nor its borders, because six decades of austerity had hollowed out its defenses."[383] Therefore, the economic state of the Dutch Republic by the early nineteenth century was one of "deurbanization, re-agriculturization and pauperization."[384] Regardless of the specific reason for this developmental decline, the Dutch economy was receding at the same time that the British experienced a stark rise in fortunes.

This does not entirely explain why the British achieved an advantage in hydraulic building by the century's end. Indeed, during the early eighteenth century it seemed as though the Dutch held the advantage related to the material and cultural factors that drive

383 De Vries and Woude, *The First*, 685.

384 De Vries and Woude, *The First*, 686.

hydraulic construction. The North Sea countries had an additional reason to transition to hydraulic building with pozzolanic materials. During the eighteenth century, a tiny creature stalked their cold waters. *Teredo navalis*, or "shipworms," would tunnel into timber and compromise the wood's strength, hence the origin of its name. Historian Richard Rhodes noted that this parasite was a major reason that English ship timbers needed to be replaced every few decades throughout the eighteenth century.[385] These worms did not prey solely on ships. They also attacked the wooden pillars that were used for docks and dikes. These parasites and the natural decay of wood caused a universal crisis along the shorelines of the North Sea empires. Most notoriously, during a storm in the fall of 1730, much of the timber in the dikes of the Dutch Republic snapped due to being filled with holes created by the burrowing shipworms.[386] This was an alarming occurrence. A contemporary observer opined that the timber palisades formed "a barrier or fortress that protects all of Holland from a dangerous enemy…as it faces the ocean."[387] The Dutch response to the shipworm crisis involved replacing the timber with stones. Gargiani records that "the stones for the new Dutch waterfront barriers are imported mainly from Norway: 'all Dutch ships that trade in the North are obliged to load a certain number of these stones as ballasts when returning.'"[388] Importing stones had its costs and,

385 Richard Rhodes, *Energy: A Human History* (New York: Simon & Schuster, 2018), 5.

386 Adam Sundberg, "Molluscan Explosion: The Dutch Shipworm Epidemic of the 1730s," *Environment & Society Portal*, *Arcadia* (2015), no. 14, from the Rachel Carson Center for Environment and Society, https://doi.org/10.5282/rcc/7307.

387 Gargiani, *Concrete*, 106-107.

388 Gargiani, *Concrete*, 111.

although the salt water invasion was temporarily halted with their use, the Dutch were also beholden to outside quarries.

Since they had ample access to a pozzolanic material, it is telling that they did not choose artificial stone to fix the issue. The Dutch had long been familiar with hydraulic cements and used them extensively in their lowland environments. An English traveler named John Carr provided a survey of some of the ways that cement was used in the Low Countries.[389] In his 1806 journey along the Rhine he observed all sorts of construction, summarized by Gargiani as, "the cement is used in Holland for masonry works along rivers and canals, for bridges, sluices, cisterns and all kinds of works in contact with water, like fountain bases, tubs, watering troughs for livestock and birds, cellars and other underground parts of buildings."[390] These were just a few examples of the advanced state of Dutch cements. In fact, Dutch *trass* was a significant export for building projects throughout the North Sea. As mentioned above, the builders of the Westminster Bridge preferred the Dutch material over the pozzolan sand available to them.

The supply of a pozzolanic material alternative proved a distinct advantage to Dutch builders. It was secured through geographic circumstance and industrial infrastructure. As late as 1791, a German master builder referred to simply as Gilly asserted that, "we may not make use of pozzolana earth, which can only be found in Italy…because it is too expensive for us."[391] They did, however, have access to a

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389 John Carr, *A Tour through Holland, along the right and left banks of the Rhine, to the south of Germany, in the summer and autumn of 1806* (Philadelphia: C. and A. Conrad and Co., 1807), 263.

390 Gargiani, *Concrete*, 75.

391 Salvatore Aprea, "German Concrete, 1819-1877: The Science of Cement from Trass to Portland" (PhD Diss., École Polytechnique Fédérale De Lausanne, 2015), 11.

substitute. The position of the Dutch Republic on the delta of major continental rivers provided access to such materials. In particular, the Rhine River passed through deposits of pyroclastic stones with similar hydraulic properties of pozzolan known locally as *tuffstein.* Gargiani found that the Germans had used this volcanic stone for local construction since the time of the Romans and limited processing of the material for cement construction existed since at least the 1600s.[392] He observed that "the importing in Holland of that material dates back at least to the 1500s and is already important in the 1600s."[393] After being processed, it would then be known as Dutch *trass* and shipped back along the Rhine and throughout the North Sea.

The use of Dutch *trass* in the same regions that supplied German *tuffstein* remained a mystery to some. A German bureaucrat expressed his confusion in 1802 when he declared that "tuff stones are transported to Holland where they are ground; then, strangely enough, they are sometimes sold in Germany along the Rhine, as if grinding tuff were a witchcraft!!"[394] There was no witchcraft, but particular advantages made the Dutch leaders in continental and oversea trades in the ground basalt. They were technological leaders due to the site of the Dutch Republic on a delta formed by multiple inland waterways and the technology used for drainage. The use of animal power and windmills to pump water also created a protoindustrial infrastructure that was applied to processing materials like German *tuffstein*. This was partially driven by the incentives of private property rights. Since the Dutch allowed for private land ownership, massive

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392 Aprea, "German," 64.

393 Aprea, "German," 65.

394 Salvatore Aprea, *German Concrete: The Science of Cement from Trass to Portland* (EPFL Press, 2016), 11.

investments went into reclaiming areas for cattle raising and dairy production.[395] Therefore, mills sprung up as land was reclaimed and then, once accomplished, applied to other applications.

This history of drainage is directly related to the mechanical advantage that the Dutch held in grinding tuff stones. In a tour of the Dutch lowlands in 1755, Smeaton observed that, "it is brought to Holland in the same state as it is taken out of the earth."[396] He described the stones "about the size of Ternaps, some great some small," were processed at a *trass* mill in Rotterdam.[397] Later in his life, Smeaton described that, "the only art that is there employed in preparing it for use is, to reduce it to a coarse powder, by means of mills for that purpose."[398] He elaborated that the process included the stones being "beat by iron headed stampers upon an iron bed, till it passes through a sieve of a certain fineness, equivalent to one of ours, having about eight wires in an inch; it is then ready for use."[399] The mills, fueled by wind or animal power provided the edge that the Dutch needed to monopolize the trade in the ground stone. The location of the Dutch trass industries supports these observations. Gargiani noted that Dordrecht became significant because it was "the site of one of the largest concentrations of windmills for water drainage."[400] "At the end of the 1700s," he concludes, "at Dordrecht there are six

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395 Richards, *The Unending*, 53.

396 John Smeaton, *A Narrative of the Building and a Description of the Construction of the Eddystone Lighthouse With Stone* (London: H. Hughs, 1791), 111.

397 John Smeaton, *John Smeaton's Diary of the Journey to the Low Countries*, 1755 (London: Courier Press, 1938), 52-53.

398 Smeaton, *Diary,* 52-53.

399 Smeaton, *Diary,* 52-53.

400 Gargiani, *Concrete*, 65.

mills for the grinding of *tuffstein*, powered by wind or horses."[401] From here, the material was sent throughout the North Sea and back along the Rhine.

As abundant as pozzolanic materials may have been in the Dutch Republic, calcium carbonate was harder to come by. Seashells had long been used as substitutes for calcium carbonate in the Dutch Republic. Although they proved sufficient in cements used on dry land, Smeaton demonstrated the deficiency of this material substitute when building in water. He wrote that, "I had heard that *Shell Lime*, that is *Cockle* or other shells burnt, set very hard and made an excellent mortar for under-drawing and inside work."[402] Nevertheless, the young engineer ran his own tests while building the Eddystone Lighthouse. "On being put into water," Smeaton found of shell based lime, "after it was set, it did not dissolve, but did not acquire additional hardness; on the contrary, by degrees it macerated and dissolved, not intentionally, but gradually from the surface inwards; and hence I concluded it totally unfit for our use."[403] For salt water building, at the very least, the seashell mortars would not suffice. The Dutch were disadvantaged without abundant materials necessary to strengthen their own hydraulic cement mixtures. This forced them to continue the ancient methods of setting stones and piling dirt to shore up their lowland empire.

Historians have yet to add the material disadvantage to the British economic and material ascendancy in the North Sea world. A pozzolan substitute had been supplied from the Low Countries since at least the sixteenth century, yet the Dutch never emerged

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401 Gargiani, *Concrete*, 65.

402 Smeaton, *Narrative*, 106.

403 Smeaton, *Narrative*, 106.

as leaders of building with cement under water. The advantage that they gained from the location of the Dutch territory was related to inland transportation routes and access to the sea. It is from this trading chokepoint that German *tuffstein* could be processed with Dutch milling technology and either sent back along the Rhine or to the markets of England. The Dutch were severely disadvantaged when it came to cement production, however. The lack of large calcium carbonate deposits left seashells as the only material for producing mortar. Although at least as durable as other cements used on dry land, it would never set as a durable material under water. This was a primary limiting factor in the material war against the waves.

The French had similar issues with securing all of the materials for large-scale application of hydraulic cement. The Canal du Midi predated the British supremacy in controlling Mediterranean sea lanes. However, beginning in the early eighteenth century, the British exerted more influence over these routes in the calm sea. By the victory in the Seven Years War in 1763, this British influence solidified.[404] This resulted in trade blockades against major imperial rivals, especially the French. When it came to pozzolan sands, the French trade persisted using illicit means such as obtaining passports for trading from other countries, including Portugal.[405] However, the French were disadvantaged by another development in 1763. "While during the entire first half of the eighteenth century, the export of pozzolana was subject only to taxes to be paid to the consuls of the various nations involved," Gargiani wrote, "in 1763 the Papal State issues

404 For a discussion of the impact of the English blockades to the Pozzolana trade, see: Gargiani, *Concrete*, 47.

405 Gargiani, *Concrete*, 55.

an edict…imposing a duty on ships using the port of Civitavecchia…the tax consists in the payment of a guard to oversee loading operations."[406] Although this was a universal tax, Gargiani observed that France was disproportionately targeted as shipments to Marseille and Agde were the most significant at the time.[407] Trade did persist to these ports, but the practice became increasingly more politicized and expensive.

The high point of pozzolan cement use in France between the Languedoc Canal and the rise of British sea supremacy demonstrated the potentials and limits of hydraulic building in the early modern period. Abundant supplies of inorganic additives could still be accessed through the ancient trade networks of the Mediterranean. They could also be applied in large-scale hydraulic building like ports and canals. That trade also depended on a number of factors that could limit supply. Due to the dynamics of colonial trade and complexity of the pozzolan supply process, substitutes could not easily be had in the European ports. In order to secure a steady supply of the volume necessary for large-scale building, the mature trade networks of the Catholic Church were relied upon. This, of course, became problematic when imperial competition or taxation disadvantaged the importing country. Without their own domestic supply of volcanic sands, the hydraulic cement use in early modern France was limited. Hydraulic building was transforming, but access to durable, abundant and waterproof building materials still dictated who the leaders in hydraulic construction would be.

The British hydraulic building ascendancy had a lot to do with material availability and imperial success. They pulled away from their continental counterparts

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406 Gargiani, *Concrete*, 55.

407 Gargiani, *Concrete*, 55.

not because of any cultural or intellectual supremacy, but due to the fossil advantage and imperial power. British sea supremacy provided abundant supplies of pozzolan sand, which proved more plentiful in Great Britain than anywhere else on the continent. Smeaton described his access to pozzolan sand from Italy as a stroke of luck directly related to this construction project. "I very fortunately learnt, that there was a quantity of it then in the hands of a merchant in Plymouth;" wrote Smeaton on finding that pozzolana sand was in port. It was originally imported for the use on Westminster Bridge, but, "having found that tarras answered their purpose, neither commissioners, engineers, nor contractors, would trouble themselves to make a trial of it, and therefore refused it."[408] Smeaton acknowledged his luck as "it might otherwise have been many months before I could have got any for trial; and afterwards as many more…before I could have got a quantity from Italy for actual service."[409] Once the pozzolan sand trade was established, it grew over the following half century due to Smeaton's endorsement and its qualities as well as low cost. The British maintained abundant supplies of each of the materials for producing hydraulic cement.

Smeaton's Breakthrough:

The British ascendancy related to hydraulic construction was not as obvious when the young John Smeaton began work on the Eddystone Rocks in the early 1750s. Even after developing his "water cements," Smeaton still used rubble for fixes. In 1763, Shortly after Smeaton's Tower was complete, the London bridge was falling down. The multiple arch stone bridge that had split the Thames River since the 13th century had

408 Smeaton, *Narrative*, 100.

409 Smeaton, *Narrative,* 100.

recently been renovated. In 1759, one large arch replaced multiple arches in the center of the bridge. Four years later, the new foundations were showing signs of collapse. Smeaton was called from Yorkshire to London by the Common Council of the City of London in March where he formulated a plan to save the bridge. Smeaton described that he had "found the depth of the water under the great arch, at low still water, to be twenty-two feet, the current making hourly depredations upon the starlings, the south-west shoulder of the north pier undermined six feet, the original piles, upon which the old works had been built, laid bare to the action of the water, and several of them loosened."[410] Unbeknownst to other builders in the city, the problem was a dramatic alteration of the river's current. Basing his investigations on the reduced power flow of the waterworks in the arches on the end of the bridge and his own depth tests, Smeaton determined the need to support the bridge's foundations in the Thames River.

Smeaton's solution involved purchasing stones from nearby contractors and throwing them into the water to reroute the flow. A chronicler of the event wrote that, "the stones were purchased that day; horses, carts, and barges were got ready, and the work instantly begun, though it was Sunday morning."[411] These stones were available in London due to expanding construction projects, which provided the volume necessary for such a large repair. "By the seasonable application of 200 tons of rubble stones," Smeaton determined, "it [the bridge] appears to be secured for the present, so that I don't

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410 John Smeaton, "The Report of John Smeaton," in *Reports of the late John Smeaton. F. R. S., made on various occasions, in the course of his employment as a civil engineer*, vol. 1, by John Smeaton (London: Printed for Longman, Hurst, Rees, Orme, and Brown, Paternoster-Row, 1812), 286.

411 Smeaton, *Reports*, xxviii.

find the structure in immediate danger."[412] Through procuring such materials in the British capital, Smeaton saved the bridge. However, he had not yet reached the point of having the supply and methods for using hydraulic cement to carry out such monumental works.

By this time, Smeaton had discovered the material that would revolutionize Great Britain's hydraulic building regime. He began the journey to that discovery in the Low Countries. Shortly before he started his legendary lighthouse, Smeaton's boots were in the mud at Dunkerque, the first stop on a tour of the Low Countries to observe their hydraulic engineering works, considered cutting edge at the time.[413] Imperial conflict was in the air. "Finding how jealous the French are of the English," Smeaton nervously wrote at this French border outpost. "Especially at this time which is looked upon as being the Eave of a War: and fearing at least my curiosity at Dunkerk might have been noticed."[414] His concern was justified. In 1698 the builder Winstanley was arrested by French privateers while constructing the first Eddystone lighthouse, for example. Although Winstanley was promptly released by King Louis XIV with the comment that "France is at war with England, not humanity," Smeaton feared a similar fate or worse.[415] Wisely, Smeaton "resolved to depart the next morning for Ypres and get out of French territory."[416] He always had a knack for knowing when to leave. His first escape involved

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412 Smeaton, "The Report," 286.

413 Smeaton, *Diary,* 2.

414 Smeaton, *Diary*, 6.

415 "Winstanley's Tower," Trinity House, accessed October 20, 2019, https://www.trinityhouse.co.uk/lighthouses-and-lightvessels/eddystone-lighthouse.

416 Smeaton, *Diary*, 6.

dropping out of law school to pursue the trade that landed him in this region of magnificent hydraulic works a decade later.

This speaks to Smeaton's temperament. He valued personal observations and shunned inherited universalisms. He must have hated a system built on precedent like English law. This does not mean that he ignored those who came before. In order to create a satisfactory mortar matrix for his lighthouse, Smeaton did study the prevailing architectural literature. He familiarized himself with popular texts of the day that modernized the Roman methods, such as French builder Bernard Forest de Belidór's *Hydraulik Architeque*. This pivotal book was read thoroughly by Smeaton, who regularly compared it to Dutch infrastructure during his mid-century sojourn.[417] Although seen as a vanguard text at the time, there was little difference between the works of Vitruvius and Belidór in relation to hydraulic cement. They suggested the use of pure limestone with pozzolan additives. Had Smeaton followed that advice to the letter, he never would have proved the value of the impure calcium carbonates along the waterways of Great Britain. True to his personality, he ran his own tests.

Other builders' failures on the Eddystone Rocks, barely visible above the waves at high tide and known to sailors as "a treacherous enemy," provided an opportunity for Smeaton.[418] The reef jutted into the sea southwest of Plymouth. Beyond the ships destroyed by the hidden stones, many projects, and lives, were lost on the rocks. During

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417 Smeaton, *Diary*, 6.

418 E. Price Edwards. "The Eddystone Lighthouse, 1882," in *The Eddystone Lighthouses (new and Old) an Account of the Building and General Arrangements of the New Tower with an abridgment of Smeaton's Narrative of the Building of the Old Tower*, by John Smeaton and T. Williams (London: Simpkin, Marshall Co., 1882), 2.

the winter of 1703, a massive storm struck the North Sea. The merchant Henry Winstanley, a few operators, and their timber and stone lighthouse were swept out to sea, never to be seen again.[419] Then, in 1708, silk merchant John Rudyard built a second lighthouse. This lighthouse burned down in 1755. The year after the fire, the Earl of Macclesfield, then President of The Royal Society, recommended John Smeaton as a competent craftsman to build yet another lighthouse.[420] The young engineer was prepared.

He set out with an eye towards what was possible. Reflecting on his choice of sand in the *Narrative of the Eddystone Lighthouse*, Smeaton noted that "I was already apprized that two measure of quenched or slaked lime, in the dry powder, mixed with one measure of *Dutch Tarras*, and both very well beat together to the consistence of a paste, using as little water as possible, was the common composition, generally used in the construction of the best water-works both in stone and brick."[421] He continued, "I had found mentioned by Belidor; and that is the Terra Pozzolana found in Italy.—I very fortunately learnt, that there was a quantity of it then in the hands of a merchant at Plymouth; which had been imported as an adventure from Civita Vecchia."[422] With access to Italian Pozzolans, he determined that this sand would suffice and used it in his legendary mixture. The shipments that Smeaton used for the Eddystone lighthouse were in watertight casks, an indication of the packaging of these valuable sands when

419 Edwards, "The Eddystone," 1.

420 Smeaton, *Narrative*, 38.

421 Smeaton, *Narrative*, 97.

422 Smeaton, *Narrative*, 109.

transported by water.[423] Although he may have been the first to use pozzolana cement in England, his choice of materials were between two that had been known as reliable hydraulic admixtures throughout the two millennia dating back to the ancient Roman discovery of such materials. Vitruvius and Belidór would have approved of Smeaton's choice of sand.

It is unknown why the builders of the Westminster Bridge refused the Italian sands. They had relatively similar qualities and could afford the same strength when used in cement.[424] Years later, Smeaton obtained those sands for a bargain price. It seems that cost played a major role in his choice of pozzolan from then on. In a letter concerning the construction of locks in Dublin, Smeaton wrote that, "I would recommend the use of pozzelana, which has been imported from Italy to several of the works that I have been concerned for in Great Britain, at the price of forty-two and forty-three shillings per ton; as it comes much cheaper than terras, it can be made more liberal use of…it will greatly contribute to the establishment of good masonry."[425] Smeaton made no mention of the comparative strength between these two materials. However, if the cost was an indication of the amount of supply, then it is clear that pozzolans formed a better alternative than manufactured sand. The volcanic zone of the Mediterranean remained the primary supply point.

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423 Smeaton, *Narrative*, 111.

424 Pasley, *Observations*, 38.

425 Smeaton, *Reports of the late John Smeaton. F. R. S., made on various occasions, in the course of his employment as a civil engineer*, vol. 3, by John Smeaton (London: Printed for Longman, Hurst, Rees, Orme, and Brown, Paternoster-Row, 1812), 183.

Smeaton's original contribution to the history of hydraulic building was related to the second ingredient of "water cements." When it came to lime, he departed significantly from the ancient tradition of Vitruvius that was repeated through Bélidor, which recommended the use of pure limestone in hydraulic building. His own discovery was born of necessity. The worksite proved challenging due to being submerged at times and constantly threatened with wet weather. In a concession to the North Sea during the building of the Eddystone Lighthouse during the 1750s, Smeaton wrote, "I always laid it down as a fundamental maxim, that on account of the precariousness of weather to suit our purposes, if we could save one *Hour's* work upon the *Rock* by that of a *Week* in our *Work-yard*, this would always prove a valuable purchase."[426] Smeaton and his affiliate, a young William Jessop who became a noted engineer in his own right, orchestrated the work as a fleet of seamen on retainer ferried the materials and workers to the reef when possible. The materials, he knew, would have to be more durable than those previously destroyed by the sea. Even though the Port of Plymouth was near the jagged reef and known for its quality limestone, Smeaton looked for alternatives.

Smeaton knew that following tradition would not suffice. If his tower were to avoid being washed away by the waves, like the others had, the strongest possible material would need to be used. Smeaton had observed that it was "generally agreed upon by masons, that mortar, if mixed up with salt water, would never harden in so great a degree, as the same kind of composition would do if made in fresh water."[427] This posed a challenge for the engineer. The base of the lighthouse would constantly be inundated

426 Smeaton, *Narrative*, 93.

427 Smeaton, *Narrative*, 93.

with salt water as the waves crashed on the rocks. The same element that prevented constant work on the Eddystone Rocks would put constant strain on whichever material he chose. “I had yet to learn,” Smeaton wrote of his persistent ignorance while preparing to build the lighthouse, “whether there would be any difference in the firmness of the mortar, on account of the lime being made from different kinds of lime-stone.”[428]

He found that mortars made in the nearby region of Aberthaw, northwest of Plymouth, was superior in saltwater building. Smeaton described that these “Aberthaw” deposits were largely ignored by agriculturalists because it “would not use it because it dried on land.”[429] This lime was all but ignored by those who made up the local population. Nevertheless, Smeaton used nearby kilns to carry out his own tests. This broke with the long held tradition of trusting the inherited knowledge of the Romans in all things material because it had impurities. Smeaton continued that the “most pure lime affording the greatest quantity of *Lime Salts*, or impregnation, would best answer the purposes of *Agriculture;* whereas, for some reason or other, when a limestone is intimately mixed with a proportion of *Clay,* which by burning is converted into Brick, it is made to act more strongly as a cement.”[430]

Smeaton’s experiments led him to conclude, “that the best lime for the *Land* was seldom the best for *Building* purposes.”[431] His distinction between lime for land and lime for building is one that was also a significant discovery as the treatises dating back to

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428 Smeaton, *Narrative*, 103.

429 Smeaton, *Narrative*, 93.

430 Smeaton, *Narrative*, 93.

431 Smeaton, *Narrative*, 93.

Cato referenced the use of lime for each. Although the exact causes of the strength were unclear at the time, Aberthaw limestone had such a mixture of roughly 86 percent carbonate of lime and 11 percent clay. In his own words, "the difference of hardness after twenty-four hours was very remarkable: the composition of two measures of *Aberthaw* to one of *Tarras*, considerably exceeded in hardness that of common lime and *Tarass*…and this difference was more apparent, the longer the compositions were kept."[432] Thus, he settled on the impure Aberthaw limes to create his legendary hydraulic cement mixture. This was a significant contribution to the knowledge of hydraulic cement production and one with particular relevance for Great Britain.

Due to Great Britain's mineral endowment, Smeaton had abundant materials to test throughout his life. Through such examinations, Smeaton provided the first detailed survey of the content of the extensive calcium carbonate deposits in England. In his *Narrative of the Eddystone Lighthouse*, published in 1791, the engineer recorded nine different types of limestone and their clay content on the soggy island. His results listing clay to calcium carbonate ratios were as follows: Aberthaw lime from Glamorganshire 3/23; Watchet lime from Somersetshire 3/25; Barrow lime from Leicestershire 3/14; Lyas lime from Long Bennignton, Lincolnshire 3/22; Clunch lime from Lewis, Sussex 3/16; Grey chalk lime from Dorking, Surrey 1/17; Berryton Grey Lime from near Petersfield, Hants 1/12; Chalk lime from Guildford, Surrey 2/19; Sutton lime from Lancachire, 3/16.[433] The existence of such a wide variety of calcium carbonate with different levels of

432 Smeaton, *Narrative*, 105.

433 Smeaton, *Narrative*, 116.

purity gained particular relevance after Smeaton's experiments revealed their value for hydraulic construction.

Smeaton was a practical man and left explaining why the clay content made for better water cements to the scientists who developed such a description much later.[434] Nevertheless, Smeaton's tests to find the best lime for water building upset the conventional wisdom "that the harder and stronger the *Lime*-stone was, the stronger would be the *lime*."[435] Although Smeaton was unwilling to comment on the scientific reasons for the strength of impure limestone, he did pose a hypothesis as to why the traditional knowledge of pure lime existed for millennia. To Smeaton, it was a matter of economy. He observed that "the workmen generally prefer the more *pure* limes for building in the *Air*, because being unmixed with any quantity of *Sand* (generally the cheaper material) into its composition, without losing its toughness beyond a certain degree, and requires the least *labour* to bring it to the desired consistence: hence mortar made of such lime, is the least expensive, and in dry work the difference of hardness, compared with others, is less apparent."[436] The persistent myth of pure lime worked for centuries in dry land building. It would not suffice when the extreme elemental strains of the sea were put on them.

Smeaton left clear instructions for the strength of the limes of Great Britain in his *Narrative of the Eddystone Lighthouse*. "The best kind of lime for water works that I know of," he concluded, "is from Watchat in Somersetshire, Aberthaw in South Wales,

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434 Smeaton, *Narrative*, 116.

435 Smeaton, *Narrative*, 116.

436 Smeaton, *Narrative*, 108.

and Barrow in Leicestershire."[437] Later, it was determined that these were all part of the Blue Lias deposit that crossed the island in a diagonal direction.[438] He noted that each of these types were "of excellent use in jointing the stones that form the lodgement for the heels of dock gates and sluices, with their thresholds, &c. when of stone." "Common lime," he also explained, "will fully answer for the faces of walls either stone or brick that are exposed to water."[439] Although England was still dependent on imports for volcanic sand, it had plenty of lime suitable for hydraulic cement. Smeaton extended that building regime under the water line.

Cement historian William Michaelis wrote of the importance of Smeaton's discovery in 1869, "not only to sailors, but to the whole human race, is this lighthouse a token of useful work, a light in a dark night. In a scientific point of view, it has illuminated the darkness of almost two thousand years."[440] This also ought to be tempered a bit. Smeaton did upset convention by proving that calcium carbonate with a small amount of clay content would prove superior as a material. However, he still relied on pozzolan and trass. Therefore, the famed hydraulic cements of the legendary engineer were simply an improved pozzolan. Furthermore, his breakthrough was only possible because Smeaton built near abundant calcium carbonate deposits and was funded to carry out imperial projects. This did, however, create a template for hydraulic building well

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437 Smeaton, *Reports,* vol. 3, 415.

438 Donaldson, "Stucco," 154.

439 Smeaton, *Narrative*, 105.

440 William Michaelis, Sr., *Hydraulic Mortars* (Leipzig, 1869), Passage quoted in: A.C. Davis, *A Hundred Years of Portland Cement* (London: Concrete Publications Limited, 1924), 14.

into the nineteenth century that was used in most major British hydraulic construction projects.

Cement and Colonies

Smeaton's Tower guided ships towards the Port of London. This was a natural port located along the Thames River, which cut through the center of the British metropolis. Evelyn noted of the advantage that the river afforded the city, "the City of London is built upon a sweet and most agreeable Eminency of Ground, at the North-side of a goodly and well-condition'd River."[441] Robert Burton, an observer during the early eighteenth century, shared this view. He wrote, "this noble river for its breadth, depth, gentle straight even course, extraordinarily wholesome waters and tides, is more commodious for navigation than perhaps any other river in the world."[442] Indeed, the Thames River afforded protection from the tumultuous seas. "Opening eastward toward France and Germany is much more advantageous for traffic than any other river in England;…and on both sides thereof lies a fruitful and fat soil, pleasant rich meadows, and innumerable stately palaces," Burton continued.[443] Evelyn noted decades earlier that "the sea flows gently up this river four score miles, that is almost to Kingston, twelve miles above London by land and twenty by water, bringing the greater vessels to London, and the smaller beyond."[444] Although it did not access the vast resources of the

441 Evelyn, *Fumifugium*, 16.

442 Robert Burton, *A New View and Observations on the Ancient and Present State of London and Westminster* (London: Printed for A. Bettesworth and Charles Hitch, 1730), 106.

443 Burton, *A New View*, 107.

444 Burton, *A New View*, 107.

continental rivers, the Thames River provided clear advantages to river traffic and the city that was served by it.

Due largely to these attributes, traffic on the Thames had long been an issue by the time of Burton's writing. Ships carrying colonial trade goods, coal and other imports all converged on the river. By the late seventeenth century, congestion was already evident in the underdeveloped riparian port. Edwarde Chamberlayne wrote in 1684 of this connection between colonial success and the transportation bottleneck:

> The vast Traffick and Commerce whereby this City doth flourish, may be guessed at chiefly by the Customs which are paid for all Merchandise imported or exported, which are but very moderate Impositions in comparison of the Imposts of most other Countries of *Europe,* and yet the Customs of the Port of *London* only amount to above three hundred thousand pounds a year: By the infinite number of Ships, which by their Masts resemble a Forest as they lye along this stream, besides many that are sent forth every year to carry and fetch Commodities to and from all parts of the known world, whereby it comes to pass, that no small number of Merchants of *London,* for Wealth, for stately Houses within the City for Winter, and without for Summer, for rich Furniture, plentiful Tables, and honorable living, *&c.* excel some Princes in divers of our Neighbor Nations: Moreover, one may conjecture at the huge Commerce by the infinite number of great well furnished Shops.[445]

Colonial riches and congestion went hand in hand on the Thames. Forests of masts had to be moved in and out of the Port of London in order to serve the city with the material wealth that Chamberlayne described. It took another century before the efficient accommodation of such massive volumes of trade.

Smiles detailed the issue with shipments in the underdeveloped port. "Before there were any public docks on the Thames, the merchandise was kept afloat in barges for want of room to discharge it at the legal quays. An Indiaman of 800 tons could scarcely

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445 Edw. Chamberlayne, *Second Part of the Present State of England Together with Divers Reflection Upon the State Thereof*, ed. 13 (London: Printed by Thomas Hodgkin, 1687), 199-200.

he delivered of her cargo in less than a month, and the goods had then to be lightered from Blackwall nearly to London Bridge," the nineteenth century historian observed.[446] Few of the necessary conditions for large-scale hydraulic building had been met in London even by the mid-eighteenth century. Imports of building materials were inconsistent and knowledge of the techniques for building in rivers was lacking. Smeaton's breakthrough in the use of cement only occurred at mid-century and took decades to become widely accepted practice. The reason for building hydraulic infrastructure and the riches to do so were achieved long before the methods and materials caught up.

This convergence of factors that increased hydraulic building in the ports was piecemeal and involved more innovations than Smeaton's cement, and more building materials too. Building in rivers presented different challenges than building in the sea. The pulse of the tides left areas below the high water mark exposed for such work. Smeaton built the lighthouse on a reef with the foundation exposed at low tide. The Thames River fluctuated, but not nearly as much as the tides. Some rivers did dry up seasonally, which left the late summer and fall as the primary time to carry out construction underneath the high water mark. Perennial rivers, like the Thames, never exposed their bottoms, which posed challenges for attaching structures to firm foundations on the bed of the river. Furthermore, the river's current proved a constant strain on any structure that was not built on a firm foundation. Whether building abutments for bridges or wet docks, the riparian environment posed unique environmental challenges.

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446 Smiles, *Lives*: *Early Engineering*, 16.

Smiles also detailed the lowly state of British hydraulic building by the eighteenth century, "bridge building also must have greatly fallen off. Little more than a hundred years ago, there were few architects or masons able to build a bridge of any extent: and when a second bridge had to be erected over the Thames at London, the French engineer Labelye, a native of Switzerland, was sent for to build it," he wrote.[447] When it came to major hydraulic engineering projects, foreign builders were called upon. This began to change in the eighteenth century as British builders became more familiar with continental methods. George Semple was a notable Irish builder with close relations to builders and their customs in London and thus provides a useful source for considering the state of British hydraulic building. He was tasked with rebuilding the Essex Bridge in Dublin whose foundations had been compromised by a deep and fast flowing river. Through his survey of bridge building technology, the meticulous engineer detailed the state of hydraulic engineering in riparian habitats in Europe Great Britain during the mid-eighteenth century.[448]

Semple wrote of the lack of proper techniques among the British at this time. In particular, the use of "coffer-dams," which Semple thought were not used in England until the building of the Westminster Bridge, commissioned in 1737 and carried out by a foreign engineer.[449] Semple felt that these methods of creating enclosed areas within rivers to expose the river bottom and set the foundations for support pillars was the key to successful building. His assumption was supported by consulting the texts of Alberti and

447 Smiles, *Lives: Early Engineering*, vii.

448 Semple, *A Treatise*, 28.

449 Semple, *A Treatise*, 31.

detailed drawings of Bélidor. Each provided depictions of a method for building coffer-dams. Smiles described the process they used as "a row of piles was driven into the bed of the river, on which a quantity of 'gravel and even mould earth mixed together' was thrown in all round the piles, with a view to render the enclosed space impervious to water. Pumping power was then applied, and the bed of the river was laid dry within the coffer-dam thus formed, after which the gravel or clay was dug out to a proper depth, until a solid foundation was secured for the piers. Piles were driven into the earth under the intended foundation-frame, and the building proceeded upward in the usual way."[450] As Smiles demonstrated, the extensive use of large timbers was absolutely essential for building in the river. Fortunately, for Semple and the builders of London's bridges, timber imports were readily available by the eighteenth century. They provided the means for Semple to incorporate the techniques of continental builders and finish his project in 1754.

Materials still needed bonded to the riverbed or to foundations made from wood pillars driven into the earth. Smeaton's cement proved useful in this regard. What Smeaton demonstrated on the Eddystone Rocks at around the same time of Semple's work was a way to create a solid masonry bond under water. His mixture became the standard for British lighthouse building shortly after this discovery and for that purpose. Smeaton stressed the importance of that underwater cement in 1767 when he detailed that any stone "such is used about the light-houses, that will bear the weather: the capping project about 2 inches on each side, and to drip towards the outside, to be laid with mortar made of lime from Barrow, in Leicestershire, or any other lime of equal quality

450 Samuel Smiles, *Lives of the Engineers With an Account of Their Principal Works* (Cambridge: Cambridge University Press, 2012), 57.

for water-works. The body of the wall to be built with lime from *Houghton*, near *Castleford*, *Yorkshire*, or any other equal quality."[451] His distinction between the foundation limes, often exposed to sea water, and the walls demonstrated the need for different materials wherever they would be exposed to water.[452] He continued to suggest the use of pozzolan for the sands.[453] Bridge pillar foundations in rivers had different challenges, but were no exception. Smeaton was unwavering in his suggestion for the proper mixture. In description of the "method of construction of the Bridge over *Stonehouse Creek*," Smeaton suggested that "it will be adviseable to set the whole outside up to high water neap tides with *Watchet* or *Aberthaw* lime, and it would, as *Plymouth,* lime is very tender in water, be also very adviseable that a quantity of the aforesaid lime was procured to mix with that of *Plymouth* lime and marble do not seem disposed to form themselves a very compact body, when constantly subject to the water."[454] Like with lighthouses, only the proper hydraulic limes would suffice for sturdy foundations underneath the water line.

The materials and techniques for building under water were available to British builders by the eighteenth century, but the problems of congestion persisted through the end of the century. Researching the condition of transportation in the river, historian

451 Smeaton, *Reports*, vol. 1, 261.

452 Smeaton discusses the use of shell lime as the probable reason for the failure of the piers at Ramsgate Harbor in the 1760s and 1770s. He noted that this was likely due to a carpenter named Mr. Ethridge who had worked the Westminster Bridge project was put in charge of the project in 1752. Smeaton believed that since he was a carpenter and not a mason, he made a critical mistake of choosing the wrong material. Rather than testing local deposits of limestone as the project's former surveyor had planned to do, Ethridge stuck with shell lime. Smeaton, *Reports,* vol. 3, 88.

453 Smeaton, *Reports*, vol. 1, 263.

454 Smeaton, *Reports*, vol. 1, 309.

Stuart Oliver found that "from 1789…a series of petitions to the Corporation complained at the state of the Thames. In October, one petition claimed the river 'is in many places extremely defective', while a second claimed its condition meant 'the greatest delays Damage and inconvenience in sending . . . commodities by Water Carriage'."[455] All of which was carried out with a system of quays for unloading onto smaller ships. Oliver continues,

> all ships from the East and West Indies and America, and from the Baltic and other European ports, had to moor in the river and off-load into lighters: the cargoes being landed at various quays…Colliers also off-loaded into lighters…only the smallest vessels unloaded directly at riverside quays. Reasonably efficient up to the mid 18th century, this system became intolerable by the 1790s from excessive delays and serious losses by plunder; with as many as 880 ships frequently at the moorings, where accommodation could properly be provided for about 600, and at some places large ships were lying 12 or even 16 abreast in the tiers.[456]

The success of imperial endeavors led to an increase in the congestion of the metropole. This became an issue for those dedicated to the rapidly and securely moving goods from the colonies to European metropoles, particularly the Port of London. Wealth extraction from the colonies depended on various infrastructure at home and abroad that propped up the seaborn networks of imperial trade.

Despite the relative stagnancy related to cement technology over two millennia, significant changes to the methods of transporting imperial goods occurred in the eighteenth century. For instance, Historian Kenneth Pomeranz described the development of port technology and its relation to imperial gains by contrasting the Indian Ocean and

455 Stuart Oliver, "Navigability and the Improvement of the River Thames, 1605-1815." *The Geographical journal* 176, no. 2 (2010), 170.

456 Oliver, "Navigability," 170.

Atlantic Ocean trade networks. In a comparison of Chinese trade in the Indian Ocean and the British Atlantic triangle trade, Pomeranz found great variation in the time spent in distant ports. Chinese junks relied on seasonal trade winds and thus spent large amounts of time trading in locations throughout the Indian Ocean. The Atlantic trade winds served as a never ending circular pattern that tied western Europe to Africa and the Americas.[457] Largely due to this coincidental convenience, the English developed a system where an agent would compile all of the colonial exports in one central location. This facilitated more rapid loading of ocean vessels than if they visited a number of different landings and traded for a period of time. Pomeranz noted that, "shipping costs fell dramatically in the Atlantic during the eighteenth-century because various groups of European shippers—who *did* pay wages to their crews, found ways to cut port time—e.g., from over one hundred days gathering cargo in the Chesapeake before returning circa 1700 to under fifty days circa 1770—and so could make two round trips rather than one."[458]

Changes to the port technology in the colonies and along trade routes is only half of the story. The increased shipping from the colonies resulted in more congestion in the metropole. This was evident in London during the eighteenth century, which experienced congestion due to the amount of ships arriving on the Thames since the late seventeenth century. By the start of the eighteenth century, shippers in London complained of the "difficulties, delays, loss of time and inconveniences" due to ship congestion in the Port

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457 Crosby, Alfred W., *Ecological Imperialism: The Biological Expansion of Europe, 900–1900* Cambridge University Press, 2015), 104-131.

458 Pomeranz elaborates when he states that, "this reduction in port time was achieved by having a local agent collect the desired goods in a warehouse before the ship arrived, rather than having the ship visit many plantations and spend time haggling." Pomeranz, *The Great Divergence*, 172.

of London.[459] It only worsened over time. In 1702, there were an estimated 1335 ships that arrived from foreign ports. By 1798, that number had risen to 3420. In the same time period, the trade tonnage nearly quadrupled from 157,035 to 627,087. The coasting trade added to this congestion. In 1700, there were recorded 5,562 ships that by 1798 had doubled to 10,133. The tonnage again increased dramatically in that period from 218,100 to 1,250,449.[460] By 1800, the Third Report on the Port of London found that in the year 1799, excluding the East India ships, 13,514 vessels from the foreign and coasting trade passed through the riparian port.[461] Unloading this volume of freight securely while maintaining the flow of ships was a monumental task.

The companies most vested in such trade took the lead in developing infrastructure for such ends. A report by the Scottish police reformer Patrick Colquhoun estimated that by the end of the eighteenth century, "The cargoes of the Weft-India ships are the principal objects of attention with the Lumpers and their associates, who are supposed to plunder from each ship not less than ten hundred weight of sugar a day, during the period of the discharge; and it is estimated by an intelligent writer, that upon Weft India produce imported (*communibus annis*) the Merchants, Ship-owners, and

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459 John Pudney, *London's Docks* (London: Thames and Hudson, 1975), 14.

460 Patrick Colquhoun, "Abstract of the *Imports* Into, and the *Exports* From, The Port of London," in *A General View of the Causes and Existence of Frauds, Embezzlements, Peculation and Plunder, of His Majesty's Stores in the Dock Yards, and Other Public Repositories and in the Naval Department in General; with Remedies Humbly Suggested for the Purpose of Preventing These Evils and Abuses* (London: Printed by H. Baldwin and Son, 1799), 215.

461 "Appendix, An Account of the Total Number of Ships, With Their Tonnage, Including Their Year 1799; Distinguishing the Countries From Whence Such Ships Repeated Voyages, That Have Entered Inwards, at the Port of London, from Foreign Ports, in the Case, With the Principal Articles of Importation From Each Country," in *Third Report From the Select Committee Upon The Improvement of the Port of London*, 24 September 1799-29 July 1800," *House of Commons Papers,* vol. 132, (July 28, 1800), 6, from Proquest: UK Parliamentary Papers, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.hcsp-002506?accountid=4485.

Planters at present lose Ł150,000 and the Revenue Ł50,000 by pillage and plunder alone."[462] The West India Company was the first to develop policing for this issue and soon turned their attention to the infrastructure itself.[463]

By the end of the century, serious efforts to rebuild the Port of London were being considered by the government and merchants alike. The first of such projects to accomplish the rapid and secure unloading of goods was the West India Docks. In the 1808 *Microcosm of London*, R.A. Ackerman described that "on July the 12th, 1799, an act of Parliament was passed, to incorporate this company, nearly twelve months previous to the legislative establishment of the London Docks, though the latter were the first projected, in consequence of the superior importance of the property of the West India planters."[464] The ill-gotten colonial gains, largely from slave labor, of the West India proprietors that included Mr. Robert Milligan and Mr. George Hibbert funded the project. It involved excavating a massive area for the use as wet docks. Historian A.W. Skempton noted, "the total excavation for the West India Docks, between 1800 and 1805, came to about 1.5 million cubic yards."[465] The docks had two main areas, one to receive loaded vessels that was "two thousand feet in length, and five hundred and ten feet in breadth…[that was] sufficiently capacious to hold from two to three hundred such ships

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462 Patrick Colquhoun, *A Treatise on the Police of the Metropolis* (London: Printed for J Mawman, 1806), 57.

463 "Appendix," 4.

464 R. Ackermann, *The Microcosm of London; or, London in Miniature* (England: Methuen & co., 1904), 219.

465 A.W. Skempton, "Engineering in the Port of London, 1789-1808," *Transactions of the Newcomen Society* 50, no. 1 (1978-1979), 93.

as are used in the West India Trade."[466] The loading area for ships heading to the colonies had similar dimensions.

The West India Docks were the first of many major projects that transformed the process of moving goods through the metropole. Various others were undertaken shortly after that, which included similar structures for the East India Docks and London Docks among others. Skempton noted that, "By 1806 the ship canal, the West India and East India Docks had been completed, and also a major part of London Docks, with vast warehouses at the London and West India. The largest fully laden ships ranged from about 500 tons in the London Docks to 800 tons in the East India. Quayside accommodation was provided for at least 200 ships, and as many more could lie at moorings within the docks. The total area of impounded water amounted to 100 acres, or 110 acres including the shallower Greenland Dock, a capacity quite without precedent elsewhere."[467] This was a radical transformation of the possibilities for moving high volumes of goods, rapidly and securely, through the Port of London. They were also extremely expensive. Skempton continued, "all of this monumental work was carried out by Capital expenditure from 1799 to 1808 totalled £4.1 million (equivalent to at least £100 million in modern terms) and the engineering work alone accounted for nearly £1.5 million. West India and London Docks, as built in 1806, rank among the half dozen largest schemes carried out in Britain at any time before 1830. The concentration of effort also can scarcely be rivalled, and the main objective was certainly achieved: London had

466 Ackerman, *The Microcosm*, 219.

467 A.W. Skempton, "Engineering," 93.

become the world's best equipped port, as well as handling the greatest volume of shipping."[468]

It took until these projects of the early nineteenth century for the cultural drivers of hydraulic construction to incorporate the cements of Smeaton. What resulted was the construction of a state of the art metropole with cutting edge cement. Skempton described the scale of building at the West India Docks, "the first brick of the dock wall was laid in June 1801 by the contractors Adam & Robertson, who also built the lock structures and warehouses. The walls, 6 feet thick with counterforts at 15 feet centres, were of brickwork throughout, set in hydraulic lime mortar."[469] This hydraulic cement was the material pioneered by Smeaton and now widely adopted for "water cements." Skempton noted that "for the dock walls and locks [of the London Docks] Rennie generally followed the designs of Jessop at the West India Docks, the differences being,…the use of pozzolana mortar for the outer brick and stone courses."[470] The architect Peter Nicholson described the materials used for many other projects in the Port of London as follows: the East London Dock using Dorking lime, the eastern entrance of the London Docks as using blue Lias lime and the New London Bridge being built with Haling lime.[471]

468 Skempton, "Engineering," 91.

469 Skempton, "Engineering," 91.

470 Skempton, "Engineering," 96.

471 Peter Nicholson, "Appendix F: The Following Table, Showing the nature and Proportion of the Ingredients in the Mortar Employed in Several English Works, will, it is presumed, be considered useful," in *The Builder's and Workman's New Director: Comprising Explanations of the General Principles of Architecture* (London: A. Fullerton and Co., 1853), 452.

The New London Bridge, completed in 1831, was the final project of the transformation of the Port of London. Many factors drove such monumental construction that included massive wet docks and state of the art bridges. All used the mixtures pioneered by Smeaton. When paired with the techniques from the continent, these materials allowed for strong bonds to the river bottom that did not deteriorate and were durable enough to withstand currents. Massive amounts of timber were also needed in this process where giant coffer dams revealed areas that could serve as foundations. This work was carried out long after Semple's studies and Smeaton's tests, but they demonstrated the unique ability for large-scale building under water. All of which was driven by the need to rapidly unload and secure trade goods from colonies around the world. This was the first example of the mineral endowment being applied to the infrastructure of a major port city.

By 1831, the Port of London demonstrated state of the art building in its docks and bridges. This scene was far removed from the quays and mud shorelines of the seventeenth century city. Such a transformation would have been much more complicated without the mineral endowment as well as the techniques, organizations and finances to carry out such monumental building. All were constructed with brick, mortar and hydraulic cement in the mineral economy. When paired with the staggering riches and power of imperial corporations, British hydraulic cement provided seemingly limitless possibilities for building in the Port of London. This rise of the British hydraulic cement regime is a complicated history that reveals the interplay between the ancient pozzolan hydraulic building tradition, European imperial systems and the British mineral endowment. Historian John F. Richards described the global impact of such western

European maritime infrastructure when he wrote that, "in large measure because of maritime improvements, a new, truly global economy coalesced. Capital investment moved readily from one world region to another. Prices for commodities quoted in the urban centers of the new world economy sent price signals to producers around the world."[472] After Smeaton, those signals were sent from a foundation of anthropogenic stone.

Cement and Canals

Adam Smith detailed another feature relevant to the intensification of the movement of goods and hydraulic building. "Good roads, canals, and navigable rivers, by diminishing the expense of carriage, put the remote parts of the country more nearly upon a level with those of the neighbourhood of the town. They are upon that the greatest of all improvements," the famous economist wrote.[473] Smith was opining at a time when waterways provided distinct advantages for moving bulk materials. Prior to the railroad, moving freight by canal facilitated the greatest volume of transport. In Great Britain, these forms of transportation were linked in a national transportation network of canals by the early nineteenth century.[474] The alternative transportation option involved overland transport with carts and/or pack animals. Together, they formed what Wrigley described as a "dendritic" network with the waterways forming the main trunk and roads branching off in various directions. Wherever this transportation web spread,

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472 Richards, *The Unending*, 1.

473 Adam Smith, *An Inquiry Into the Nature and Causes of the Wealth of Nations* (London: T. Nelson & Sons, 1852), 62.

474 Hadfield, *The Canal Age*, 35-36.

communities and environments were transformed.[475] Hydraulic cement was essential for this process of development as durable and waterproof materials were used extensively for locks, bridges and aqueducts.

Wrigley expanded on his description of the pre-rail canal networks. He wrote, "in order to reach an urban market the grain must journey first along the twigs to reach the small branches and then the larger boughs before reaching a main trunk of the system."[476] When manufactured products needed to move in the opposite direction, they would start on a trunk line and be carried to the outer twigs. Even before the spread of canals, rivers were used in similar networks. This can be seen with the transportation of lime to the countryside. Daniel Defoe observed of the banks of the Thames:

> From these Chalky Cliffs on the River-side, the Rubbish of the Chalk, which crumbles away when they dig the larger Chalk for Lime, or, (as we might call it) the Chips of the Chalk, and which they must be at the Charge of removing to be out of their way, is bought and fetch'd away by Lighters and Hoys, and carry'd to all Ports and Creeks in the opposite County of Essex, and even to Suffolk and Norfolk, and sold there to the Country Farmers to lay upon their Land; and that in prodigious Qunataties, and so is it valued by the Farmers of those Counties, that they not only give from two Shillings and Six Pence, to four Shillings a Load for it, according to the distance the Place is from the said Chalk-Cliffs; but they fetch it by Land-Carriage Ten Miles, nay Fifteen Miles up into the Country. This is the Practice in all the Creeks and Rivers of Essex, even to Malden, Colchester, the Nase, and into Harwich Harbour up to Maning-tree, and to Ipswich; as also in Suffolk, to Albro, Orford, Dunwich, Swold, and as high as Tarmouth in Norfolk. Thus the Barren soil of Kent, for much the Chalky Grounds are esteemed, make the Essex Lands Rich and Fruitful, and the mixture of Earth forms a Composition, which out of Two Barren Extreams, makes One prolifick Medium; the strong Clay of Essex and Suffolk is made Fruitful by the soft meliorating melting Chalk of Kent, which fattens and enriches it.[477]

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475 Cronon's "Second Nature" provides a way to conceptualize that change in *Nature's Metropolis: Chicago and the Great West* . 1st ed. (New York: W. W. Norton, 1991), 62.

476 Wrigley, *Path to Sustained Growth,* 136.

477 Daniel Defoe, *A tour thro' the whole island of Great Britain, divided into circuits or journies* (London: JM Dent and Co, 1927), 10-11.

The Chalk of Kent and Essex, so despised by builders, was spread throughout the surrounding countryside in a process of agricultural intensification facilitated by material availability. These zones spread across Great Britain by the completion of the national canal network.

Although roadways were essential for this process, there were clear advantages to the amount of goods that could be accessed through water trade. Skempton compiled records from Smeaton and his colleague Thomas Telford to demonstrate the transport possibilities involved with various methods at the turn of the nineteenth century. The tonnage available per transportation method were demonstrated as follows: average packhorse, 1/8th; stage wagon, soft road, 5/8th; barge on river, 30; barge on canal 50.[478] Besides volume, there were considerations to be had that were related to the properties of each method of transportation. Smeaton understood that the use of water transportation networks was not always profitable. “Suppose that lime-stone gravel from the deep cutting at the Downings is to be had for nothing, it is yet to raise and to wheel on board a vessel; the expense of wear and tear, or hire of vessel is to pay, and the men’s wages to attend to it, and horses to draw it.”[479] He concluded that, “it is very true, that carriage from great distances in general, is cheaper far by water than by land, but for small distances it is not.”[480] The reliability of the chosen route also had to be considered. For instance, Historian W.T. Jackman wrote of the roads and concluded that “the evidence went to show that the roads were so bad as to be ruinous and impassable in winter; that

478 Results of these experiments are recorded in: A.W. Skempton, “The Engineers of the English River Navigations, 1620-1760” *Newcomen Society Transactions*, Vol. 29, (1953), 25.

479 Smeaton, *Reports,* vol. ii, 273.

480 Smeaton, *Reports,* vol. ii, 273.

the heavy loads of lime, woolens, wool, corn, coal, etc., cut the roads so as to make them impassable."[481] Nevertheless, their usefulness for reaching the "twigs" of the dendritic system remained.

Canals had many advantages over roads and, in most cases, rivers and streams as well. The increased volume of trade that could be transported on these routes was clear in Smeaton and Telford's tests. Another advantage was that they avoided the inconsistent terrain of natural water courses. This was not completely without disadvantages, however. Historians Derek Aldcroft and Michael Freeman astutely observed that, like roads, "canals may have avoided the shoals and rapids of rivers, but they were far more liable to frost stoppage in subzero weather and water shortage in dry."[482] This was particularly obvious in the industrial cities that included Liverpool and Manchester. Jackman wrote of the difficulties "especially at certain seasons, to provide food for so large a population, for it must be remembered that the working classes seldom have the means which will enable them to lay up in advance for their future needs, but must obtain their sustenance week by week. In the winter season, when the roads were bad, and sometimes closed, the price of food rose exorbitantly."[483] There were still clear limits to the transportation networks that tied together industrial cities and the countryside, but the zones of development changed dramatically with the building of canals.

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481 W.T. Jackman, *The Development of Transportation in Modern England* (Cambridge: Cambridge University Press, 1916) 89.

482 Derek Aldcroft and Michael Freeman, *Transport Revolution in the Industrial Revolution* (Manchester: Manchester University Press, 1983), 2.

483 Jackman, *The Development*, 358.

Cement was absolutely crucial to the growth of British canal networks that began with an estimated mileage of around 1400 in 1760 and expanded to over 4000 by the mid-nineteenth century.[484] One such account of the importance of cement for canal construction comes from the building of "the Bridgewater Canal," a pioneering project that connected Manchester to larger canal networks.[485] Arthur Young recorded the challenge that presented itself to James Brindley, the chief engineer, and how cement was used to overcome it.

> In carrying on the navigation a vast quantity of masonry was necessary, in building aqueducts, bridges, warehouses, wharfs, &c. &c. and the want of lime was felt severely; the search that was made for matters to attempt to burn into lime, was a long time fruitless; at last Mr. Brindley met with a substance of chalky kind, which, like the rest, he tried; but found (though it was of a limestone nature) that, for want of adhesion in the parts, it would not make lime….casting it in moulds like bricks, and then burning it; and the success was answerable to his wishes: In that state it burnt readily into excellent lime; and this acquisition was one of the most important that could have been made.[486]

In what may have been the first instance of the domestic manufacture of a durable and hydraulic cement in Great Britain, Brindley was able to turn calcareous mud into usable lime. Other canal builders, without access to similar domestic supplies, relied on the import of *trass* or *pozzolan* to build the infrastructure of the early canal networks similar to its applications in the Canal du Midi. Cement provided the necessary material for spreading the canal networks throughout Great Britain.

The example above demonstrated how the canals of the late eighteenth century were built, but not the motivation to build them. Smeaton understood the ability of these

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484 Hadfield, *The Canal Age*, Appendix i.

485 Smiles, *Lives: Early Engineers*, 356-358.

486 Smiles, *Lives: Early Engineers*, 359-360.

networks to reorganize the social organization and transform the environments wherever they spread. He explained:

> The same difficulty and cost of transport checked the growth of nearly all other branches of industry, and made living both dear and uncomfortable….About a hundred and fifty pack-horses, in gangs, were also occupied in going weekly from Manchester, through Stafford, to Bewdley and Bridgenorth, loaded with woolen and cotton for exportation; but the cost of the carriage by this mode so enhanced the price, that it is clear that in the case of many articles it must have acted as a prohibition, and greatly checked production and consumption. Even corn, coal, lime, and iron-stone were conveyed in the same way, and the operations of agriculture, as of manufacture, were alike injuriously impeded.[487]

Smeaton acknowledged the role of canals in hastening the intensification of production, a central feature of industrial development. Without the materials to build such a network of water transportation routes, the areas bought to serve the interests of industrial capital would have been much reduced.

Traditionally, investors and engineers are spotlighted as driving this process with little mention of the British material endowment. These canal networks could not have been built without the access to abundant amounts of hydraulic cement. This could not have been accomplished without access to coal and calcium carbonate. Great Britain's canals increased access to each of these mineral materials. Much has been written on the increased access to coal provided by such canals. Indeed, accessing coal was a significant reason for their funding. Writing in the mid-nineteenth century, economist William Stanley Jevons argued that "until coal supplied the purpose, there was not spirit enough in this country to undertake so formidable a work as a canal."[488] Many contemporaries agreed with Jevons. C. Beaument wrote in 1789 that "the numerous canals, and

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487 Smiles, *Lives: Early Engineering*, 427.

488 W. Stanley Jevons, *The Coal Question* (London: Macmillan and Co., 1865), 105.

conveyances from the distant part of the kingdom, and to local stations, owe their existence to the wealth of the acquired by the use of coal."[489] Coal had obvious importance for industrial cities that used it for energy.

There were many more incentives for connecting the city and countryside, however. In a discussion of the "expediency of opening the temporary Cut and Lock near *Dalderse*, from the canal of *Forth* and *Glyde* to the river Carron." Smeaton wrote, "the utility of this cut, from Carron shore and parts adjacent, appears from its first construction, which was to bring the stones got from the quarries at and near *Kinnaird*, and brought down by the coal waggons to *Carron* shore, there put on board small lighters, was brought through the temporary cut, and brought to build the first land lock, and other works in that quarter; also the lime, pozzolana, and timber were brought for some time that way."[490] Smeaton sensed the broader connection of the increased movement of all types of bulk materials as driving the canal boom. The canals did move the coal necessary for industrial production, but also the materials necessary for building industrial habitats. They even opened up access to timber reserves that had not yet been exploited due to the area needed to transport them.[491] Wherever the canals stretched, the movement of fossil fuels and transformation of built environments intensified simultaneously.

No other example of the relation of building materials to the industrial development encouraged by canal boosters can be demonstrated than by those promoted

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489 Beaumont, *Treatise on the Coal Trade*, 2.

490 Smeaton, *Narrative*, 407.

491 Albion, *Forests and Sea Power,* 323.

by James Watt. The famed improver of the steam engine was also concerned with navigation on the *Forth* in 1767. In an appeal, "that a navigation may be opened at a small expense from the valuable woods, lime and slate quarries of *Abersoil* to the bridges of *Abersoil* upon the *Forth*." Watt outlined the benefits of such a project

> Suppose an aqueduct bridge of a proper dimension, erected across the *Forth,* betwixt these two points, (the distance being 300 feet) there will be dead water from *Frew* to *Lint* mill-dam, by which the upper part of the *Forth* will have an easy, short, and open access to the *Devon* collieries, and also have an opportunity of dropping into the tides-way at *Cambus*, by locks of 14 ½ feet fall, the advantage of which, considering how much lime-stone, slates, wood &c. must come down, and how much coal must go up the *Forth*…a great length of navigation, and the loss of time in waiting for the tide, will be saved, is extremely obvious.[492]

Here was the network that could be had. Once a canal was opened up, the areas with access connected the bulk materials from different zones. These transportation routes were essential for increasing the materials available for use in building and industry.

Building materials and energy were not the only items that moved along these industrial pathways. Industrial cities also needed food from the countryside. As discussed in Chapter 2, the growth of urban sectors was directly related to the increased yields of the domestic agriculture per acre. Smeaton wrote that, "all sorts of produce were brought to the latter town, at moderate rates, from the farms and gardens adjacent to the navigation, whilst the value of agricultural property was immediately raised by the facilities afforded for the conveyance of lime and manure, as well as by reason of the more ready access to good markets which it provided the farming classes."[493] Canals provided the link for the simultaneous growth of town and country.

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492 Smeaton, *Narrative*, 148.

493 Smiles, *Lives: Early Engineering*, 402.

The benefits for bulk material shipment were clear. For instance, Jackman observed that, "in 1777, two years after the opening of the Trent and Chesterfield Canal, the cost of carriage on this canal for lime, coal and other heavy articles, was asserted to be around one-fifth of the expense of the usual land carriage."[494] Looking to the countryside, another decrease in cost was possible. "Then, too, manure, lime, marl, and other things for fertilizing the soil, could be conveyed at slight expense and used for bringing into cultivation the poorer and waste lands, all of which were necessary for furnishing food products to the continually increasing industrial population," Jackman continued.[495] The areas around the canal then developed in ways that incorporated materials, food and fuel into sprawling networks that lowered the price of goods and increased their use.

Smeaton described the profitability that such canals could afford in a survey of the gains provided by the Bude Haven canal. Inadvertently, he outlined the transformation to the land as well. His estimation was presented as follows:

> The quantity of sand and lime likely to be carried annually upon the canal, wherein he observes, that the distance between Brude Haven and Kelly Rock, in a right line, according to Martin's map, is twenty-eight miles, and he supposes that an equivalent surface to that of five miles on each side this direct line, that is, a surface of twenty-eight miles long, and ten miles broad, will receive benefit from this canal; in consequence, 179,200 acres of land will be concerned therein, of which he supposes one-twentieth part, that is, 8960 acres yearly, to be broken up for tillage. He supposes further, that one half of this, viz. 4480 acres, to be manured with sand, and other half with lime, and that the value of carriage of each may be estimated upon what it is at Launceston, which is nearly half-way between the two extremes…the usual quantity of lime laid upon an acre is 100 Winchester bushels, weighing about 3 ½ tons, the land-carriage of which to or

494 Jackman, *The Development*, 456.

495 Jackman, *The Development*, 456.

> near Launceston in one pound sixteen shillings, this will be ten tons to three acres…The estimated capital for the execution of this work is Ł119,210, and the capital that is likely to be supported by the tolls upon sand and lime is Ł145,192, which exceeds the former by no less a sum than Ł25,990; and hence, upon the first face of it, it would appear a practicable scheme.[496]

This is an important feature of the canal networks. Recall Smith's observation of transportation routes elevating "the remote parts of the country more nearly upon a level with those of the neighbourhood of the town."[497] His observation was one that put high value on the intensification of development. Whether or not this was a positive development is debatable. For many, isolation from the zones of intensive production could have been dear and comfortable. Nevertheless, all features of the agrarian landscape seemed to transform wherever the canals spread. For instance, Smiles observed that, "the owners of land discovered that their breed of horses was not destroyed, and that their estates were not so cut up as to be rendered useless, as many of them had prognosticated. On the contrary, the demand for horses to carry coals, lime, manure, and goods from the canal depots, increased rapidly."[498] Even animal husbandry increased in these rural zones of agricultural intensification.

Wherever the trunks of the artificial dendritic networks stretched, the environment and economy was transformed. Much has been written about the movement of coal on these networks, but this was a much larger process that involved the movements of various goods. Lime, *pozzolan*, *trass*, timber, food and much more transported in great volumes on these networks. All were used to create the built landscape of

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496 Smeaton, *Reports,* vol.1, 413-414.

497 Smith, *An Inquiry*, 62.

498 Smiles, *Lives: Early Engineering*, 462.

industrialization where densely populated cities could be sustained with goods from the surrounding countryside. The countryside could also access goods that were manufactured in the towns, notably the movement of agricultural lime brought new agricultural areas into use. Canals were yet another piece of hydraulic infrastructure, built by cement, that facilitated rapid and intensive industrial development.

Conclusion:

The rise of British hydraulic engineering during the eighteenth century and the transformation of the Port of London in the early nineteenth demonstrated more than just British ingenuity. It was the result of British trade supremacy, abundant supplies of calcium carbonate that could be used in hydraulic cement and the ability to marshal the techniques, organizations and finances for such an endeavor. It was part of a European revival of the pozzolan sand trade. When paired with the impure calcium carbonate of Great Britain, these volcanic sands created an inorganic hydraulic cement limited only by the movement of materials. This material afforded the transformation of the Thames River and the city of London into a modern metropolis through its use in building wet docks and the foundations for bridges. It also facilitated the spread of canal networks across the island by 1800. Such intensification of hydraulic building had an impact on the slaves and forced laborers that enabled British material take-off. Colonies and coal were essential features of the British great divergence. Hydraulic construction using British cements formed the infrastructure for each of these drivers.

CHAPTER FIVE

CEMENT

Introduction

On September 16, 1792, John Smeaton labored not on building, but in his garden. The aged builder suffered a stroke that day and soon passed away. Aware of the prevalence of this cause of death in his family, Smeaton knew that day would come. He had remained intellectually active until then. Smeaton's written account of the construction of his most enduring work, *The Narrative of the Eddystone Lighthouse*, was in production up to that fateful moment. Beyond merely a treatise on his most famous monument, the tract included a discussion of his experiments on cement over the previous four decades. Smeaton recorded a major regret in this sweeping commentary on hydraulic engineering. "I wished to examine all those limes which discovered any degree of fitness for *Water Building*; and more especially, if possible, to find out a substitute for Tarras and Puzzolana in this kingdom; that we might be in possession of *all* the best materials for water building within ourselves: and…I have not succeeded with respect to the latter, so far as my ardent wishes led me to hope," he lamented.[499] Always looking forward, Smeaton sensed that a domestic substitute for volcanic sands was key to Britain's own cement transition. Tragically, his health prediction came shortly before one was found. British "natural cement," first patented in 1796, provided a durable, quick-setting and waterproof cement that could be produced without imported volcanic sands. The new cement greatly expanded the possibilities of the Industrial Revolution.

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499 Smeaton, *A Narrative*, 114.

This foundational material of the modern age was first patented by James Parker. He and Smeaton had little in common. Smeaton was an engineer; Parker was a clergyman. Smeaton was calculating; Parker was a doer. Smeaton left many records; Parker left very few. Smeaton dropped out of college; Parker earned a doctoral degree in medicine. Smeaton worked for the advancement of building; Parker was a patent hunter. Numerous biographies and letters described Smeaton's life and death; Parker's life remains a mystery and he died in obscurity. Smeaton was enshrined by his fellow engineers as a pioneer in the history of cement; Parker has largely been forgotten. Smeaton never broke free from the ancient western European cement tradition; Parker did. Each were products of their unique time and place. Neither lived to see the transformation brought by the domestic substitute for ancient Roman cement mixtures.

The discovery of the cementitious properties of natural cement stones occurred at a time when British boosters and builders were searching for such a transformative material. Parker's patent was lodged at the dawn of the Industrial Revolution, already set in motion on infrastructure made of cement. Parker would have witnessed the dramatic changes in Great Britain enabled by the liberal application of cement in urban areas and through the construction of ports, bridges and canals. Recognizing the connection between building materials and technological possibilities, Pasley wrote in 1838 that "cement is as much a modern invention as the steam engine."[500] His confusion must be excused.[501] Roman cement only became widely utilized after the expiration of Parker's

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500 Pasley, *Observations*, xv.

501 It would be hard to locate exactly what he meant. Cement broadly conceived had an ancient history. By Pasley's time, the term "cement" signified Parker's Roman cement, which was patented in 1796.

patent in 1810. Nevertheless, the increased use of Roman cement coincided with industrial development across Great Britain.[502] In the decades after 1810, building with cement was increased due to the domestic supply of abundant natural cement.

Since Parker's Roman cement did not require imports of sand to obtain hydraulic properties and increase strength, its production was free from the need to import bulk materials. Its production with fossil fuels also maintained freedom from the organic economy. Each factor facilitated the sustained mass production of the material in Great Britain. Roman cement had two further attributes that gave the bonding agent an edge over its ancient namesake. The new cement set much faster than its predecessor. One of the challenges to building in water included the action of waves or rivers. This complicated building as hydraulic cement could, and often was, washed away before setting. On dry land, a challenge to masonry building included the settling of bricks in slow setting mortars and an inability to set in cold temperatures. In each case, Roman cement was an improvement over earlier, relatively slow-setting, mixtures. The second distinct attribute of Roman cement was its strength. Parker's cement was far more durable than the poor quality mortars that preceded it. When paired with the material's local abundance, these qualities transformed the possibilities of British building.

The lack of a requirement of volcanic sands also freed the manufacturing of abundant, durable and hydraulic cement from the western European building regime. No longer needing *trass* or *pozzolan*, such materials could be economically produced wherever natural cement stones and fuel could be accessed. Due to this happenstance, building similar to that which helped support the British Industrial Revolution could be

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502 Von Tunzelmann, *Steam Power.*

carried out around the world. The antebellum northern United States most demonstrated this transferable property, particularly through natural cement's use in canal construction. Industrial Historian Robert Lesley wrote of this early history of the cement industry, "it is evident that the development of the canal system of the United States in the early days therefore went hand in hand with the development of the American Natural Cement Industry."[503] Often overlooked as a crucial piece of the networks that spread industrialization from the northeast, westward, the natural cement stones of the Appalachian range facilitated a replication of the artificial water routes that British industrialization so relied upon.

By affording an abundant, durable, quick-setting and hydraulic cement free from the western European building regime, natural cement revolutionized the possibilities of the built world. Parker's patent did not emerge in isolation. Cement had been used to create the conditions for industrial development in Great Britain well before his patent. The fire-resistant buildings, hydraulic infrastructure and canals of the island formed the runway for economic take-off. Coal, colonies and cement formed the transformative technological troika that afforded the intensification of production associated with modern industrial societies. These features were increased through the liberal application of natural cement. The new material facilitated seemingly limitless building of docks, bridges, tunnels and other industrial structures. The British system of industrial lithic building was also freed from the western Europe by no longer relying on pozzolanic materials. The early industrial northern United States demonstrated this diffusion as many of the antebellum canal networks were built with natural cement. Parker had created a

503 Robert Whitman Lesley, *History of the Portland Cement Industry in the United States* (New York: Arno Press, 1972), 14.

material that changed the possibilities of global development at the moment of industrial take-off in the UK and US. Natural cement as used to begin a process of lithic development that has since transformed the world.

Parker's Patent

Parker lived in an environment of intensive building and conveyance of goods. At the time of his patent, his residence was recorded at Christchurch [i.e. Lambeth], Northfleet. This area was in the heart of the industrial zone of London and near the river complex of the Thames and Medway. It was a region transformed by coal and colonies. The location was also at the upstream end of the water route that brought limestone from Kent and Essex for the notoriously low quality lime kilns of London. His patents sought to capitalize on this material and manufacturing abundance. The first was for a "*Method of Burning bricks, Tiles, Chalk* [with] a certain material never before made use of for burning bricks and tiles, and calcining chalk, earth, stone, and limestone."[504] This turned out to be peat, a poor substitute for cheap coal. His second patent served as the founding document of the modern lithic epoch, British Patent 2120, lodged by Parker in 1796, for "A certain Cement or Terras to be used in Aquatic and other Buildings and Stucco Work."[505] Parker's cement was made from domestic supplies of "cement stones" and produced a hydraulic, durable and fast-setting cement. Parker's patent freed British

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504 James Parker, Method of Burning bricks, Tiles, Chalk [with] a certain material never before made use of for burning bricks and tiles, and calcining chalk, earth, stone, and limestone, British Patent 1806, filed May 17, 1791, reproduced in *Patents for Inventions: Abridgements of the Specifications Relating to Bricks and Tiles* (London: Published at the Great Seal Patent Office, 1862).

505 James Parker, A certain Cement or Terras to be used in Aquatic and other Buildings and Stucco Work, British Patent 2120, June 28, 1796, reproduced in "Parker's 'Roman Cement' Patent," accessed June 4, 2021, https://www.cementkilns.co.uk/cemkilndoc006.html.

builders from the reliance on pozzolan imports and greatly expanded the building possibilities on the island.

Ironically, Parker chose the name "Roman cement" for his new creation. Although the name elicited the thought of the grand Roman buildings in the imaginations of prospective buyers, few considered this a replica of the ancient material. The material that Parker used was made from natural cement stones that could be found in various geologic layers of the London Clay. These stones were exposed wherever the river or waves cut away at the shorelines of southeastern England. Prior to the invention of Roman cement, no builder thought of these stones, scattered about under cliff sides or on beaches as a valuable commodity. Historian A.P. Thurston explained that "the use of such cements, a recent discovery made in this country, was entirely unknown, not only to the Romans, but to all other nations, until Mr. Parker's time."[506] Writing shortly after its widespread adoption in Great Britain, noted engineer Charles Pasley claimed that "the natural cements of England [are] most improperly and absurdly termed Roman cement."[507] He was correct. The cements pioneered by Smeaton and used in the hydraulic infrastructure throughout the metropole were essentially inorganic versions of the ancient material. Parker's cement was different in its makeup, production and properties. It was a completely new building material. One with seemingly limitless possibilities.

Parker was clearly motivated by the promise of industrial riches as his patents sought to break into the thermal industries of the building trades along the Thames. How exactly Parker was able to discover the cementitious properties of the natural cement

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506 A.P. Thurston, "Parker's Roman cement," *Transactions of the Newcomen Society*, Vol. 19 (1939), 193.

507 Pasley, *Observations*, x.

stones along the riverbanks and shorelines of southeastern Great Britain, ignored by the Romans, is less clear. One, possibly apocryphal, account of this discovery was recalled in an anonymous pamphlet from 1830. True or not, it is worth reproducing in its entirety.

> It was first discovered by the Rev. Dr. Parker in the year 1796 and like many other of our most useful acquisitions, was purely accidental. When on a visit to the Isle of Sheppey, he was strolling along under its high cliffs on the northern side and was struck with the singular uniformity of character of the stones upon the beach and which were also observable sticking in the cliffs here and there. On the beach, however, the accumulation of ages, they lay very thick. He took home with him two or three in his pocket and without any precise object in view, threw one on to the parlour fire from which in the course of the day it rolled out thoroughly calcined. In the evening he was pleased to recognize his old friend upon the hearth, and the result of some unpremeditated experiments with it has been the introduction to this country of a strong, durable and valuable cement.[508]

Regardless of the legitimacy of the tale, it demonstrated the abundance of the natural cement stones that could be found along the riverbanks and shorelines of Great Britain at the time of Parker's patent. These stones afforded the substitute that Smeaton never found.

Parker's patent detailed these materials and the process for turning them into cement. An abbreviated version is provided below:

> NOW KNOW YE, that I, the said James Parker, in pursuance of and compliance with the said proviso in the said recited Letters Patent contained, do, by this present instrument, declare that the principle and nature of my said Invention, and the manner in which the same is to be performed, is described and ascertained as follows (that is to say):—
>
> The principle and nature of the said Invention consists in reducing to powder certain stones or argillaceous productions, called noddles of clay, and using that powder with water, so as to form a morter (*sic*) or cement stronger and harder than any morter or cement now prepared by artificial means. I do not know of any precise generical term for these noddles of clay; but I mean by them, certain stones of clay, or concretions of clay, containing veins of calcareous matter, having frequently, but not always, water in the center, the cavity of which is

508 Dylan Moore, "About 'Roman' Cement," accessed June 4, 2021, https://www.cementkilns.co.uk/roman.html.

> covered with small chrystals of the above calcareous matter, and the noddles agreeing very nearly in colour with the colour of the bed of clay in or near which they are found. These noddles, on being burnt with a heat stronger than that used for burning lime, generally assume a brown appearance, and are a little softened, and when so burnt and softened become warm (but do not slack) by having water thrown upon them and being reduced to powder after burning, and being mixed with water just sufficient to make into a paste, become indurated in water in the space of an hour, or thereabouts. Any argillaceous stone, then, corresponding with this description, whether known by the name of noddles of clay, or any other name, is the sort and kind only that I mean to appropriate to my own use in the fermentation of my cement.
>
> In witness whereof, I, the said James Parker, have hereunto set my hand and seal, this Twenty-seventh day of July, in the year of our Lord One thousand seven hundred and ninety-six.
>
> JAS (L.S.) PARKER.
> Signed, sealed, and delivered by the within-named James Parker, in the presence of
> JN^o^ DYNELEY, of Gray's Inn.
> THO^s^ LOGGEN, Basinghall Street.[509]

Although vague on specific details, the patent outlined a material and production processes unknown before the patent.

The most obvious difference from earlier cements involved the self-contained cement source found in the "noddles" of clay around London. Parker was unaware of the "precise general term" for these cement stones, but that mattered little. They existed in ready abundance. A work on the *Geology of England & Wales* published in 1822 described the deposits in relation to the London Clay, "Wherever this clay is visible in the form of a cliff, or has been perforated in sinking wells, it has uniformly been found to contain nearly horizontal layers of ovate or flattish masses of argillaceous

509 Parker, B.P. 2120.

limestone…[that] have obtained the name of Septaria."[510] There were large deposits of this raw material exposed in the cliffsides along the Thames and the shorelines of southeast England. The *Transactions of the Geological Society of London* included the following passage on the natural cement stones, "The long cliff of the London Clay extending along the northern side of Sheppey Isle furnishes abundance of septaria, from which that excellent material for building under water and for stucco, is made, and which is known by the name of Parker's Cement."[511] The passage also revealed the natural forces that exposed abundant supplies of the stone for the taking. "Being separated from the clay by the action of the sea, they are collected on the beach, and exported to various places where they are calcined and ground," it concluded.[512] No quarrying was necessary for the production of natural cement in and around London.

The chemical properties of the material were identified by Sir Humphrey Davy and reproduced in Edward Cresy's *Encyclopedia of Civil Engineering*. His entry stated that the natural cement stones were "45 percent clay and 55 percent carbonate of lime."[513] This was considerably more clay content than other limes that were used at the time. For instance, the Aberthaw limes identified by Smeaton contained around 15 percent clay.[514] Unbeknownst prior to Parker's patent, the high clay content removed the need for *trass* or *pozzolan* to produce durable and hydraulic qualities. In fact, it had to be used on its own.

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510 William Daniel Conybeane, *Outlines of the Geology of England and Wales* (London: Printed and Published by William Phillips, 1822), 26.

511 Conybeare, *Outlines*, 27.

512 Conybeare, *Outlines*, 27.

513 Edward Cresy, *Encyclopaedia of Civil Engineering* (London: Longmans, Green & Co., 1865), 721.

514 Smeaton, *Narrative*, 116.

Pasley noted that, “cement is always weakened by the addition of sand, whereas every kind of lime is improved by it.”[515] This provided a distinct benefit over earlier hydraulic cement mixtures in that it could be produced without imports. The production of durable and hydraulic cement had been freed from the production practice maintained since ancient Roman times.

Parker also indicated that he used higher temperatures than usual to produce cement. He claimed that the production process required “heat stronger than that used for burning lime…then burnt in a kiln or furnace (as lime is commonly burnt) with a heat nearly sufficient to vitrify them.”[516] Despite the origin legend stating that firing of Septaria stones could occur in a fireplace, significant energy sources and the kiln were likely necessary for achieving these temperatures. It is not known for certain what the exact temperature was used to produce Roman cement. Since time immemorial, the temperature for converting calcium carbonate to lime was between 800 and 1000 degrees Celcius.[517] Vitrifaction occurs at over 1200 degrees Celcius. Prior to modern cement production processes, these temperatures were thought to overburn cement and kill all cementitious properties—so they were avoided. Therefore, the temperatures that Parker used to produce his cement were likely in the 200 degree Celcius window outlined above.[518]

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515 Pasley, *Observations*, 30.

516 Parker, B.P. 2120.

517 Kingery et al., “The Beginnings of Pyrotechnology, Part II,” 221.

518 Henry Reid, *The Science and Art of the Manufacture of Portland Cement* (London: E. & F. N. Spon, 1877), 18.

Parker also indicated that the kilns used to reach such temperatures were similar to lime kilns. In an article from the first edition of *The Builder Magazine* from 1842, state of the art of lime kiln technology was described. "The segment of an egg in the direction of the axis, is the best form for a kiln: its base ten feet, and height twelve feet, or even fourteen feet, will burn 150 bushels of lime every twenty-four hours…and consume, according to the hardness of the chalk, one bushel of coals to four or five of lime," a passage on lime and mortars outlined.[519] These kilns were similar to those that had been built since Cato the Elder's description two millennia earlier. Well past mid-century, kilns for making cement and lime remained flare, or static, kilns.[520] Although the fire could be kept alight indefinitely and finished materials drawn gradually, this was a process that still involved stacking calcium carbonate and fuel in alternating levels and burning in batches. Nevertheless, these industrial ovens helped reach the temperatures necessary to convert natural cement stones into cement.

The firing process also required abundant supplies of energy. Fortunately, this was plentiful in the regions where cement was produced in London. Francis noted that "coal was initially used, coke being substituted after the introduction of gas-lighting and its availability from a local gas company."[521] Calcium carbonate and coal were each used in the production of coal gas. Lime was used to purify the gas before it could be used for heating, cooking and lighting in the city.[522] Coke was also a byproduct of making coal

519 "Dissertation on Limes—Their Properties, and Explanation in Making Their Kilns, and Burning," in *The Builder*, vol. 1 (London, 1842), 186.

520 Burnell, *Rudimentary Treatise,* 31.

521 Francis, *Cement Industry*, 36.

522 Hunt, *A History*, xxxvi.

gas. This created a fuel with a high carbon density that was readily available to the cement burners. Burnell described that "there is then an evident advantage in the employment of coke, for the gases which the latter gives off during combustion, arrive at once at their highest degree of temperature."[523] Coke provided a better alternative than coal as high temperatures could be reached faster. Nevertheless, the fuel source's relative abundance was still the driving force behind its widespread adoption. Regardless of whether coal or coke was used, the fossil advantage was again leveraged to produce abundant supplies of cement along the Thames.

In many ways, the new cement production process had similarities to British iron production at the time. Prior to the eighteenth century, the two were distinct thermal industries. Iron required firewood and grinding, which was most efficiently done by rapids in rivers. Cement could be produced with coal and did not require grinding. This allowed cement to dominate the urban material industry and required iron production to be located in rural areas. These dynamics changed by the Industrial Age. Abraham Darby pioneered a method for producing iron with coke fuel that eventually facilitated an increase in British iron production during the final third of the eighteenth century.[524] Coke freed iron production from the organic economy, but was weakened by the impurities of the fuel. In the early nineteenth century, calcium carbonate was added to

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523 Burnell, *A Rudimentary*, 20.

524 Sierfele, *Subterranean*, 115.

coke and iron ore in hot blast furnaces. Lime removed the Sulphur impurities, which greatly increased the quality of the British iron.[525]

Durable iron production in the mineral economy was mastered at around the same time that cement required an added mechanical step. Parker noted that natural cement stones "become warm (but do not slack) by having water thrown upon them and being reduced to powder after burning." [526] This required that the material be "reduced to a powder by any mechanical or other operation." Burnell wrote of the technological progression to achieve this, "in the early days the mill-stones were driven by tide or wind mills or alternatively were horse-operated, steam engines being introduced later."[527] This added an extra step in the production process, that, if operated by water would have restricted the production sites for cement as it had iron over centuries. The steam engine allowed for cement production to remain free from such spatial limits. By the early nineteenth century, the major cement mills of Great Britain resembled other thermal industrial technology in fuel source and grinding—notably iron.

Edward Cresy's encyclopedia described the finishing process, "in the mill for grinding this cement, the materials are thrown by a labourer into a sieve containing seventeen wires to an inch, which is shaken by the machinery attached to the steam engine, after which it is packed into casks and kept ready for use."[528] Rivington's *Notes on Building Construction* documented that "Roman cement is usually sold in

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525 Landes described the hot blast system as one of the most important development of the Industrial Revolution in, Landes, *Unbound Prometheus,* 92.

526 Parker, B.P. 2120.

527 Francis, *Cement Industry*, 36.

528 Cresy, *Encyclopaedia,* 722.

casks" that weighed 245 pounds.[529] The advice to builders was to keep the cask "carefully closed and dry, otherwise the cement will absorb carbonic acid and become inert."[530] Parker provided the description of how it was to be used.

> To compose the cement in the best and most advantageous manner, I take two measures of water and five measures of the powder thus described; then I add the powder to the water, or the water to the powder, taking care to stir and beat them during the whole time of intermixture; the cement is then made, and will set or will become indurated in ten or twenty minutes after the operation has ceased, either in or out of water…and the sooner the mortar or cement is used after being made, the stronger and the more durable it will be.[531]

Selling the cement required more than the ability to produce and package it. Parker seems to have joined the business of Samuel Wyatt shortly after his invention in order to market the product. This afforded an established business to sell the cement. Historian A.J. Francis recorded that "from 1798 London directories also included the following entry: Parker & Wyatt. Cement and Stucco Manufacturers. Bankside."[532] A description of their venture was also reproduced by Francis. "Writing in 1809, J.B. White says that Wyatt was Lord of the Manor of Minister in Sheppy," Francis explained, "which he had purchased for Ł4,000, and was in contract with the Lord of the Manor of Warden for the supply of stone from that area. He owned no land in Essex but had private contracts with local landowners who were unaware of the value of the stone he was taking away and for which he was paying them about

529 Rivington, *Notes on Building Construction*, Part III: Materials (London: Rivingtons, 1879), 158.

530 Rivington, *Notes on Building Construction,* 158.

531 Parker, B.P. 2120.

532 Francis, *Cement Industry*, 35.

Ł10 or Ł12 per 50-ton barge load."[533] Throughout the 14 year life of the patent, few had caught on to the value of the material that before was seen as completely useless.

The lack of awareness of the value of the cement provided a benefit when obtaining natural cement stones, but hindered its sales. In order to demonstrate the value of the stones to consumers and habituate builders to its use, a process of commodification needed to occur. This was begun as early as the patent was lodged. The patent itself could be seen as a sort of marketing propaganda, but more soon followed. This involved branding the new cement. "Roman cement" was first used to describe the material in a pamphlet on "Roman Cement, Artificial *terass* and Stucco," published in 1796.[534] No respected builder thought it to be an actual Roman cement. For instance, Pasley wrote that it was "most absurdly named."[535] Nevertheless, invoking the Roman material signaled to the consumer the qualities of durable and hydraulic cement, which Parker's Roman cement certainly was.

The quality of the material supported such a claim. Parker advertised to all prospective buyers that Roman cement was approved by the noted engineer Sir Thomas Telford. The same year of the patent, Telford was tasked by the directors of the "British Society for Extending the Fisheries and Improving the Sea Coasts of this Kingdom" to report on the new cement. His letter was published in the pamphlet produced by Parker in 1796. Before reproducing Telford's letter, it reminded the reader that "the cement is used in the construction of Locks, Aqueducts, Bridges, Arches, Pavements, Reservoirs, Floors,

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533 Francis, *Cement Industry*, 35.

534 Francis, *Cement Industry*, 30-31.

535 Pasley, *Observations*, xvi.

Wells, and other works, intended to contain water, and the stucco for the usual purpose of stuccoing buildings."[536] Telford was quoted as stating that "the directors will, I am convinced excuse my going beyond what was the strict meaning of their directions required, as I was glad to embrace this opportunity of doing justice to a discovery which may become of considerable importance to the public, and which appears to merit its attention."[537]

"Despite Telford's backing," wrote the historian A.P. Thurston, "the cement came into use but slowly; it is doubtful whether, during the life of the patent—it expired in 1810—it was used to any extent for engineering work."[538] However, Parker never lived to see the full impact of his patent that only occurred after it expired. A footnote in *The Life and Times of Telford*, written by a contemporary of Telford, stated that "Parker invented the cement, well named by him Roman Cement at the close of the last century; but the discovery was not at first productive, and, having sold his patent to Mr. Samuel Wyatt, he emigrated to America and soon died there."[539] After the patent expired in 1810, the manufacture of British natural cement expanded dramatically. Francis identified that Pigot's commercial directory 1822/23, "one of the earliest directories to have a classifieds trades sections" listed 11 different manufactures with one notable maker left out.[540]

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536 Francis, *Cement Industry,* 32.

537 Francis, *Cement Industry*, 32.

538 A. P. Thurston "Parker's 'Roman' Cement," *Transactions of the Newcomen Society* (1938): 195.

539 John Rickman, *The Life of Thomas Telford* (London: James and Luke Hansard & Sons, 1838), 135.

540 Francis, *Cement Industry*, 64.

By this time, natural cement was also produced in multiple locations. This was largely due to material availability. Geology texts from the period supported this observation and recorded that "these masses abound so greatly that they have been considered as being characteristic of the London Clay; but it is not the only one of the English beds which contains them."[541] The abundance of such cement was described in an 1835 survey of industrial locations across Great Britain by George Head. "Returning home towards Whitby, I observed, adjoining the sea-shore, a manufactory for cement, prepared from a peculiar sort of stones or boulders, found imbedded in the alum-shale: the process merely consists in burning the stones in a kiln, and then grinding them," he wrote.[542] Another significant area with abundant stones could be found included Harwich. Redgrave records that in 1802, cement maker Robert Frost "discovered that the stone on the beach near Harwich belonging to the Ordnance Department had similar properties."[543] Regardless of where the natural cement stones could be found, their exploitation seemed to follow a similar pattern. Parker and Wyatt were able to simply collect the stones at low tide. During the first few decades after Parker's patent, the material for making natural cement in London were plentiful and exposed by the natural forces of the waves throughout southeast Great Britain. Over time, the easily accessible stones became scarce. This caused a shift in the major supply of cement to Harwich where large kilns churned out supplies of natural cement used in London and across the island.

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541 Conybeane, *Outlines*, 26.

542 George Head, *A Home Tour Through the Manufacturing Districts of England, in the Summer of 1835* (London: John Murray, 1836), 282.

543 Thurston, "Parker's," 197.

Francis documented that "the Board of Ordinance had a cement mill at Harwich since the year 1818."[544] In a description of royal kilns at Harwich from Cresy's *Encyclopaedia*, the kilns were described as follows, "circular, 17 feet in diameter from out to out, and about 21 feet 6 inches in height: an inverted cone occupies the middle, which has a clear diameter at top of 8 feet, and at bottom of 5 feet 6 inches."[545] The encyclopedia estimated that it would hold "a charge of 30 tons of broken cement-stones measuring 26 cubic feet to the ton, as well as fuel required for burning it….the coals and cement-stones are arranged in alternate layers, each about a foot thickness: after it has been lighted three days, the lower part may be drawn, and then by constantly filling up, this may be done every twenty-four hours: the cement-stones and coals are thrown in from the top, and every ton of cement-stone yields 21 bushels of cement powder."[546] This process, although carried out on a large scale, was still adhering to the flare or static method pioneered much earlier.

The massive production of cement at Harwich did require another method for obtaining the stones: dredging. This practice was observed by George Head on his return from Whitby as well. "The stones, all round and smooth, having been taken from below highwater mark, are shot from the vessels which bring them overboard into the sea at high-water, as near the land as possible, whence they are carted, at low-water, to the kilns," he wrote.[547] This was necessary at Harwich as well. In an

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544 Francis, *Cement Industry*, 61.

545 Cresy, *Encyclopaedia*, 721.

546 Cresy. *Encyclopaedia*, 721.

547 George Head, *A Home Tour,* 283.

investigation into the cement supply at Harwich, Admiral T. Byam Martin asked the a local, Captain George Deane, in 1844, “What number of boats are involved in the cement trade?” Deane responded, “sometimes 200 or 300, but they chiefly come from Kent; but few belong to the place; sometimes there are 100 and sometimes there are 200 ships employed; they come and go as they please.”[548] Despite the depletion of the easily accessible natural cement stones, their recovery from the sea sustained the British natural cement industry.

Parker’s patent came at a time of energy and material abundance and its production system matured with other industrial technologies. The discovery of the cementitious properties of the natural cement stones in southeast Great Britain provided a domestic substitute for pozzolan cement. Branded as “Roman cement,” the material made from the bountiful, and previously overlooked, noddles of clay and calcium carbonate along the riverbanks and shorelines of Great Britain provided a distinct substitute for its ancient namesake. Although the stones exposed above water at low tide were depleted by mid-century, extensive dredging continued to supply the British natural cement industry with its primary raw materials. Parker’s patent was yet another example of the benefits provided by the British fossil endowment. Although its discovery, mass production and application took time to develop, Parker’s Roman cement served the seemingly insatiable demand of British Builders throughout the early nineteenth century.

The Natural Cement Transition

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548 UK Parliament, House of Lords, *Harbours of Refuge: Report of the Commissioners Upon the Subject of Harbours of Refuge, to the Lords Commissions of the Treasury* (London: Printed by W. Clowes and Sons, 1845), 107, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.hol_00876-000001?accountid=4485.

Skempton observed that "in building and civil engineering work between about 1810 and 1850, the word "cement" meant Parker's "Roman" cement."[549] This was not only due to the abundant supply of the material and successful marketing. Roman cement replaced its ancient predecessor due to three specific attributes—it was waterproof, strong and quick-setting. All three properties were valued for building subaquatic infrastructure, subterranean works and dry building. Each of these sectors expanded greatly due to the economic boom of the early nineteenth century. Cement facilitated such growth. It was used extensively in hydraulic construction that included canals, harbors and ports; urban building that supported the industrial landscape of dense populations of laborers working in fire resistant cities; and railroads that required bridges and tunnels. In each of these cases, Roman cement provided the material to rapidly transform the industrial possibilities in Great Britain during the early nineteenth century.

As mentioned in the advertising literature discussed above, Parker's Roman cement gained high praise from engineers early on. Thomas Telford's endorsement to the "British Society for Extending the Fisheries and Improving the Sea Coasts of this Kingdom" was the first indication of its superior qualities related to hydraulic building. Alexander Gibb's biography of Telford recorded that the noted engineer felt "fully justified in recommending to the Directors to use Mr. Parker's Composition, in the place of Dutch Terass, in constructing of the Pier of Lochbay in Sky."[550] Gibb continued, "Telford's report, after most careful tests and comparisons, fully endorses the maker's claims, and the cement was specified by Telford in both the big aqueducts on the

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549 Thurston, "Parker's," 195.

550 Gibb, *The Story of Telford* (London: Alexander Maclehose & Co., 1935), 268-269.

Ellesmere Canal and most of his harbor works." Perhaps his most noted work, the Chirk Aqueduct, finished in 1801, was made with "hard burnt bricks laid in Parker's cement."[551] Each of his accomplishments demonstrated the utility of Roman cement.

Telford was not the only engineer to make extensive use of the cement for such purposes in the early years of its adoption. In an 1812 report to the crown on "Woods, Forests and Land Revenues," John Rennie recommended that "the joints of the brick-work should be fine, and where the water is to be let soon into the Sewer they should be made with Roman cement."[552] The same report included canal commissioners noting that their "several Bridges to be [built] of Bricks, covered on each side with Parkers Cement."[553] The material was also incorporated into more major hydraulic works. In a review of a report on an examination of "Telford's Report and Survey on the Communication Between England and Ireland by the North-west of Scotland," Lietenant General Vyfe confirmed that the best material for use at Port Patrick was "Parker and Go's. Roman cement, which hardens instantly, and will prevent the sea from washing out the lime grout while it is hardening."[554]

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551 Gibb, *The Story,* 35.

552 John Rennie, "A Report, Presented on May, 1807, to the Commissioners of Sewers for the City and Liberty of Westminster, and Part of the County of Middlesex, Suggesting Means for the Improvement of the Drainage of that District, Now Drained by King's Scholar Pond," in *Report on Woods and Land Revenue*, printed by UK Parliament: House of Commons (4th June 1812), 111, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.1812-003132?accountid=4485.

553 "Conditions on Which the Commissioners of His Majesty's Woods &c. Are Disposed to Recommend the Application of *The Regent's Canal Company* to the Favourable Consideration of Government," in *Report on Woods and Land Revenue*, printed by UK Parliament: House of Commons (4th June 1812), 111, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.1812-003132?accountid=4485.

554 UK Parliament, House of Commons, *Select Committee to Report by T. Telford for Facilitating and Improving Communication Between England and Ireland from Carlisle by N.W. Scotland* (15th June 1809),

The hydraulic properties of Parker's cement were nothing new. In fact, debate remained well into the nineteenth century about whether or not Lias lime formed a better hydraulic cement.[555] Parker's cement did provide an advantage due to its fast-setting properties, however. Parker was specific about quickly using this cement because of this quality. "Great attention should be paid to the working up of the mortar, and that no more is worked up at a time that can be used in ten minutes after it is made," he advised.[556] Telford's tests recorded that "it seems evident that a cement made of Mr. Parker's composition sets and hardens to a very considerable degree in water in the course of twenty minutes."[557] The engineer also described that slow-setting cement "may prove of much consequence in a situation where the storms are sometimes very violent, and may happen during the time the pier is building, and while the common lime mortar would not otherwise set sufficiently and resist their force."[558] Parker's cement was able to set before being washed away, which was necessary in hydraulic building that was often threatened by the waves or the flow of rivers.

Due largely to this quality, Parker's cement had clearly gained a high reputation for use in all of the hydraulic works that had been carried out with impure lime and *trass* or *pozzolan* beforehand. This was evidenced in the largest metropolitan

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24, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.1809-001937?accountid=4485.

555 James Wylson, "Elementary Essay on Mortar and Cement," *The Builder,* Vol. ii, (1843), 226.

556 Parker, B.P. 2120.

557 Telford letter reproduced in Thurston, "Parker's," 194.

558 Telford letter reproduced in Francis, *Cement Industry*, 30-31.

engineering project carried out at the time, the building of the Thames Tunnel. Engineered by Marc Brunel, it involved extending a tunnel underneath the Thames River in London. Although the project was not complete until 1842, the Thames Tunnel Company was established in 1824 and tests on materials proceeded shortly after.[559] The work was completed with brick and Roman cement. An 1827 progress report on the project revealed the scale of work, "the consumption of bricks is from 60 to 70 thousand per week with about 350 casks of cement."[560] Building with massive amounts of brick and mortar in the metropole had a long tradition, but these building conditions were unique.

Digging under the Thames involved slowly progressing through areas that would be flooded with water and pressured by sand. Brunel was steadfast in his insistence on the use of Roman cement for such a task. In a letter from 1827, he wrote that "I have no hesitation in saying that in the construction of the Tunnel we cannot introduce any other substance than Roman cement of the best quality."[561] One of the reasons that this material was so important involved the quick-setting properties of the cement. Since building was carried out in an environment where pressure and moisture was present, like the waves that could wash away slow setting cement, Brunel demanded a fast setting bonding agent. Confirming Brunel's assumption, Major-General Sir Charles William Pasley of the royal engineers was convinced that "if the use of this admirable material had not been discovered, the execution of the Thames Tunnel would have been impracticable, for if it

559 Francis, *Cement Industry*, 44-45.

560 Francis, *Cement Industry,* 47.

561 Francis, *Cement Industry*, 46.

had been attempted in the very best mortar, the pressure of earth would have crushed some parts of the brickwork before the mortar got consolidated, and in other parts the lime would have been washed out of the joints, as was the case in a new basin in Chatham Dock-yard."[562]

Pasley was concerned with such properties due to his position with the royal engineers. He spent much time trying to convince the British government of the superiority of natural cement for hydraulic works. "The Aberthaw or blue lias lime, one of the strongest limes in the world, was and is well known in England, but as hydraulic mortar, it was immediately superseded by cement, for all private works of importance, as soon as the latter came into the London Market," Pasley noted.[563] However, he continued, "now as there was in those days a much greater difficulty in prevailing on the public to adopt any thing new, than there is at present. In the public works of this country, on the contrary, whether executed by Government or by great commercial companies, cement has been less employed even for brick work, by the Engineers intrusted with the direction of them: and in masonry it has never been used at all."[564] His reports on cements did much to convince government builders of the quality of Roman cement.

Parker demonstrated the superiority through a discussion of the material's unique strength. This was confirmed to him by observations of the construction of the Thames Tunnel. Pasley described an instance where he "had an opportunity of observing in the

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562 Pasley, *Observations*, 37.

563 Pasley, *Observations*, xi.

564 Pasley, *Observations*, xi.

beginning of the present year, 1836, when the brick work laid in cement, with which the head of the Tunnel had been blocked up during the temporary suspension of the work, was cut away in order to continue the excavation. In this operation, which was exceedingly laborious, the solid bricks themselves were more frequently fractured than the cement joints."[565] This was a significant difference from the mortars that were of notoriously low quality in and around the city. Carrying out his own tests, Pasley confirmed that "it appears that pure cement is more than four times as strong at the same age, as the customary mixture of cement and of sand in equal parts by measure, which is in common use in and near the metropolis."[566] After over five centuries, Parker's Roman cement finally afforded a durable cement in the city.

Another demonstration of the strength of the material was carried out at the Thames Tunnel work site that is of world historical significance. In an attempt to demonstrate the strength that could be afforded by the new cement supported by "hoop" iron, two cantilever arches were built extending out from a central pier. Pasley described the project as resembling branches extending from, "the trunk of a tree, one of which is 60 feet and the other about 37 feet long…and this last is loaded at its extremity with a weight of 62,700 lbs."[567] This massive structure demonstrated the scale of building and strength that could be afforded completely without any organic material inputs. This was only possible with natural cement as Pasley noted, "unless cement had the property of setting almost instantaneously, and thus combining brick work properly supported into

565 Pasley, *Observations*, 38.

566 Pasley, *Observations*, 127.

567 Pasley, *Observations*, 39.

one solid mass, having the joints and bricks of equal strength, the hoop iron could not possibly communicate such extraordinary stability to the same kind of brickwork hanging in the air."[568] Although Parker's cement could not be mixed with sand and therefore did not make a suitable material for concrete, this was an early predecessor to today's reinforced building with anthropic stones.

An interesting occurrence of this monument to fossil building was that it collapsed in the severe winter of 1838. Severe frosts were known to weaken mortars and frequently led to collapse. Pasley visited the site with the suspicion that the cold weather was to blame, but was assured by Brunel that "no part of the brick or cement work was injured in the slightest degree by the frost, and that the fall of the semi - arches was solely occasioned by the foundation of the central pier."[569] This was a unique occurrence as mortars were susceptible to ruin from frost and also did not set in winters. Cold weather limited what was possible before the advent of Roman cement. Natural cement further lent itself to use in all seasons as it could withstand the coldest of winters. In addition to strengthening buildings, it also removed the seasonal requirements of brick building.

Natural cement clearly displayed attributes that were useful for builders in the city. Nicholson revealed the setting time out of water where, "on a clean mortar - board put a quantity of cement, sufficient to serve the time the cement requires to set in (about 15 minutes)"[570] This allowed for rapid construction with durable and fire resistant

568 Pasley, *Observations*, 39.

569 Pasley, *Observations*, 242.

570 Peter Nicholson, *The Builder's and Workman's New Directory* (London: J. Taylor, 1834), 102.

materials. Pasley recognized these attributes as well. "By the use of cement for example, the temporary houses of Lords and Commons were finished in a dry wholesome state ready for use, in the short space of three months after they had been destroyed by fire in 1834, though the work was executed in a very unfavourable season," he observed.[571] The fire at the temporary houses exemplified the persistent need for fire resistant building and the properties of Parker's cement meant that it could be done relatively quickly. Another driver for using such material included the British building codes that sought to prevent fire and support durable building. They mandated that walls "shall be constructed of good sound well-burned bricks, or good sound stone, properly bonded and set in good and well-compounded mortar or cement, except such woodwork as may be necessary for plates, girder or joist ends, partition heads, or for bond or chain timbers."[572]

Not everyone was impressed with the new material. In the architect Alfred Bartholomew loathed the lack of craftsmanship that the material allowed. He complained that "Parker's cement alone, is now supposed to contain all the virtues of former architectural science, and to render unnecessary the true adjustment of the arches and the other once-material parts of edifices, and the still necessary parts of buildings."[573] He felt that "Architectural Dynamics and Parker's cement are now mortal enemies." The disgruntled builder continued in a description of the structures built by it, "the truth is,

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571 Pasley, *Observations,* 40.

572 UK Parliament, *Metropolitan Buildings: Bill for Regulating the Construction and the Use of Buildings in the Metropolis and its Neighborhoods* (1844), 88, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.hol_00816-000002?accountid=4485.

573 Alfred Bartholomew, *Specifications for Practical Architecture* (London: John Williams, 1840), Ch. LXI.

they are un-geometrically absurd; they depend upon nothing but the tenacity of the cement, or the violent friction of the bricks one against another; even if they otherwise escape fracture, the slightest settlement at the foundation is sufficient to destroy the whole of them in a building."[574] This was nothing new. Critiques of British building was perhaps the only thing that Roman cement could not cover up.

Despite Bartholomew's criticisms, the cement transition was well underway by the 1830s and even government uses had adapted by the 1840s. "I am persuaded that the use of cement is not only increasing in England," Pasley wrote in 1838, "but that it will in time supersede the most approved hydraulic mortars in other countries also, for works of importance exposed to the violent action of the sea."[575] James Wylson's 1844 essay on cements and mortars in the *Builder* stated that "it has entirely superseded the pozzolana and tarras…, so long and extensively used in forming our water cements."[576] All of these commentators described the transition that had met all of the necessary conditions of building in Great Britain. It was waterproof, fire-resistant and could set rapidly with durability being an added benefit.

By mid-century, all of the conditions for the building material transition had been met and Parker's Roman cement was the premier building material. The mass production of the material was afforded by the plentiful cement stones and the energy and technology to burn it. Its qualities as a hydraulic, strong and fast-setting made it the preferred material for large-scale building during the British Industrial

574 Bartholomew, *Specifications*, Ch. LXIII.

575 Pasley, *Observations,* xix.

576 Wylson, *Elementary*, 227.

Revolution. Starting with Telford, the material was used for canals, aqueducts, bridges ports and all of the infrastructure that launched the British industrial age. Its use the Thames Tunnel and in building works in the city demonstrate the transformative nature of the material that could quickly be deployed against the elements. Demand for its use in such projects grew alongside the ability to access it on these early transportation networks. All of which were related to perhaps the most transformative technology of all, the railroads.

Cement and Steam

The relationship between Roman cement and industrialization can be imagined as part of a technological complex known by Warde et al. as "the development block."[577] Typically, coal and iron are recognized as the two primary materials necessary for such industrial development.[578] Clearly they cannot be separated in relation to the steam engine, locomotives and steam ships. Few, however, consider the importance of cement for building the infrastructure necessary for such technologies. Steamships required docks and canals, locomotives required tunnels and bridges, and steam powered factories required fire-resistant buildings. Without abundant amounts of cement being used to rapidly build such large-scale infrastructure, as cement historian Francis astutely observed, "a considerable number of the great engineering projects of the early nineteenth century could not have been carried out whilst the progress of the Industrial

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577 Astrid Kander, Paolo Malanima, and Paul Warde, *Power to the People: Energy in Europe over the Last Five Centuries* (Princeton: Princeton University Press, 2014).

578 Sierfele, *Subterranean*. And Robert Marks, *The Origins of the Modern World: a Global and Ecological Narrative* Lanham, Md.: Rowman & Littlefield, 2007).

Revolution would undoubtably have been retarded."[579] In Great Britain, natural cement was an essential material of the first modern industrial society.

The widespread adoption of Parker's cement came after the canal building boom in Great Britain. Hadfield recorded the increase in mileage of inland navigation from 1,398 in 1760 to 3,074 in 1800. Over the next forty years, the miles of the inland navigation system only increased to 4,003.[580] Although this was still a considerable extension and large canal projects, notably the New Caledonian Canal, used abundant amounts of Roman cement for locks, it was hardly the trebling of mileage achieved in the second half of the eighteenth century.[581] This was partially due to the substitution of the railroad as the preferred method for transportation. Roman cement was a foundational material for that change as well. The use of steam locomotives began in the early nineteenth century and evolved into a boom in railroad construction by the 1830s and 40s. The British railway boom reached a peak in the 1840s. In roughly twenty years, as an 1849 report by the railroad commissioners noted, "at the commencement of the year, 3816 miles of railway were open for traffic. During the year the opening of 1191 miles of railway has been sanctioned by the Commissioner, of which 751 miles are in England, 289 miles are in Scotland, and 151 miles are in Ireland, making the whole extent of railway communication at the end of the year,

579 A.J. Francis' *Cement Industry 1796-1914* (Devon, UK: David and Charles Publishers, 1978), 3.

580 Hadfield, *Canal Age*, Appendix i.

581 *Encyclopaedia Metropolitana*, vol. 23, eds. Edward Smedley, Rev. Hugh James Rose and Henry John Rose (London: B. Fellows and J. Rivington, 1845), 208.

5007 miles"[582] Building a national railway system was a massive undertaking that radically transformed the possibilities of moving goods in Great Britain. This began a positive feedback loop related to industrial scale cement production, use and transportation.

There is no clear start date for the British "railroad age," but George Stephenson's "Rocket," built in 1829, is widely regarded as the first modern steam locomotive. He and Robert Stephensons accomplishments related to the railroad engines are well-known. Few, however, consider the technology used to build the networks that they moved on. From very early on, Roman cement was an important technology for constructing railroads. Francis noted that Robert Stephenson used Roman cement for "the Kilsby and other tunnels on the London to Birmingham Railway (the first long-distance railway out of London) and for the foundations of his tubular bridge over the Menai Strait (the Britannia Bridge)."[583] The Stephensons were not unique; durable material was used extensively in all other early nineteenth century railroad construction as well. The British engineer Marc Burnell noted that "railroads, and the constructions they necessitate, have modified very materially the science of construction. In England, especially of late years, works have been executed which so immeasurably surpass in boldness anything which had been previously attempted, that we may be justified in expressing our surprise that so few attempts have been made to ascertain the real nature of the materials dealt with."[584]

582 UK Parliament, House of Lords, "Railways: Report to her Majesty of the Commissioners of Railways of 1849" (London: Printed by Clowes and Sons, 1850), 5, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.hol_01082-000002?accountid=4485.

583 Francis, *Cement Industries,* 49.

584 Burnell, *A Rudimentary*, iv.

Roman cement afforded such boldness. Historian Henry Reid acknowledged that, "the Thames Tunnel could not have been made but for the advantages it [Roman cement] secured," but also observed that "…many of the early railway tunnels were built with it as a cementing agent."[585] Pasley remained an influential figure in the history of railroad building. By the early 1840s, he had been appointed as the inspector of railways. This was shortly after his experiments with hydraulic cements and his expertise with the material served him well. For instance, his description of damage to the Box Tunnel for the Great Western Railway largely resulting from frost in 1845 made clear the importance of the material for tunnel masonry. He wrote, "as last Winter has sufficiently proved what Parts of the natural Rock are the most liable to Degradation from this Cause, the only Thing necessary to render the Tunnel perfectly secure for the future, is to line those small Portions of the Roof where the said Exfoliations took place with Arches of Brickwork laid in Cement, which the Engineers of the Company have already begun to do in a judicious Manner."[586] He continued to explain that Roman cement would resist the frost and therefore it was essential for the year-round maintenance of the tunnel. "I conceive therefore," Pasley concluded, "that small shafts with connecting drifts should be sunk, in order to get at these land-springs (tor such I believe them to be), and to turn off the wet from the brick-work of the tunnel. It is to me a matter of regret that all those portions of the

585 Reid, *The Science,* 29.

586 Charles Pasley, *Copy of Major General Pasley's Report of his Inspection of the Box Tunnel on the Great Western Railway on the 17th April, 1845*," prepared for the UK Parliament, House of Lords (17th April, 1845), 3, https://parlipapers-proquest-com.ezproxy1.lib.asu.edu/parlipapers/docview/t70.d75.hol_00891-000049?accountid=4485.

tunnel were not originally built with good cement, which sets land-springs or wet at defiance."[587]

Pasley also suggested the use of natural cement for its strengths in railroad bridges. To his surprise, a collapse of a railway bridge in the same year was not caused by faulty masonry. He wrote, "I saw no Symptoms of Cracks or Settlements in any of the Brickwork, and no Subsidence in any of the Woodwork of the Bridges or Viaducts, and therefore I beg leave to confirm my first favourable Opinion of their Safety, the only one that failed having been perfect in its original Construction."[588] Collapses were common and Pasley investigated many. What was unusual about this instance was that the collapse could not be blamed on the poor quality materials used in building the bridge. Lower quality materials and rushed workmanship were almost always to blame. This was reflected in his other reports. In one survey, he wrote that "from personal curiosity, [I] examined this tunnel, and having previously examined a bridge on the same line near Gosport, which had fallen down after the centres were struck, owing, as I found, to bad cement having been employed in building it, I was doubtful of the quality of the brick-work employed in the tunnel, and apprehensive that bad mortar or cement might have been used there also, which might lead to the failure of some part of the tunnel, and to the

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587 Pasley, *Report on Box Tunnel*, 3.

588 Charles Pasley, "Second Report of General Pasley on the Gosport Branch of the South-Western Railway," in *Report of the Officers of the Railway Department to the Right Honourable the Earl of Ripon, president of the Board of Trade For the Year 1842*, printed for UK Parliament (London: Clowes and Sons, 1843), 173, https://parlipapers-proquest-com.ezproxy1.lib.ase.edu/parlipapers/docview/t70.d75.hol_00781-000007?accountid=4485.

stoppage of the communication, even if not attended with personal danger or injury to the passengers."[589]

Pasley remained unwavering in his requirement of the use of natural cement in tunnels and bridges, each had to withstand unusual strain. His advice was clear at every survey of structural work exposed to water or pressure; natural cement was the only safe option. Pasley stated this plainly in his recommendation for building works, "pure cement (I mean unmixed with sand) of the best and strongest quality, to be done by careful and skilful workmen, accustomed to the use of that material, which is not understood by every bricklayer."[590] The early reports from the 1840s demonstrated the use of alternative cements, sometimes to devastating ends. By the mid-1840s, the surveys on the conditions of the railroads demonstrated uniform application of natural cement in bridges, viaducts, tunnels and other infrastructure.[591] This was no guarantee from failure, as Burnell reminded his readers in 1855, "unfortunately in England we do everything in such a desperate hurry, especially since railroads have been constructed, that we can not afford the time necessary for a perfect execution of the works."[592] However, natural cement afforded a durable material for the networks that spread steam across the countryside.

This was only one part of the transformation involved with cement and the railroads. The revolution in transportation method could also ship more and more cement—thereby driving up production. Typically, this was demonstrated in a transition

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589 Pasley, "Second Report," 173.

590 Pasley, "Second Report," 173.

591 Pasley, "Second Report," 173.

592 Burnell, *A Rudimentary*, 73.

from casks to sacks for packaging. Rivington's 1875 *Notes on Building Materials* described that the "sacks measure 3 feet and 7 inches by 2 feet, and contain 3 trade bushels—i.e. 210 lbs."[593] Savings and delivery to the consumer were considerable with this change. Writing at the end of the century about the American railroad cement delivery process, Uriah Cummings wrote that "nearly all the cement works of this country are located on the lines of railroads, and by reason of car shipments, the expensive wood packages are fast being supplanted by cloth and paper sacks as a substitute for wood packages."[594] He continued, "this innovation proved successful, as is evidenced by the fact that about $4,000,000 barrels of cement are sold annually in paper sacks, resulting in a saving to the consumer about $650,000 annually, this sum representing the difference in the cost between paper and wood packages."[595] It is difficult to determine the exact amount of cement that was moved on railroads in early nineteenth century Great Britain because it was often classified with other materials. However, it is clear that material was used to build such transportation networks and adapted to delivery by rail at an early date.

By the middle of the nineteenth century, natural cement was well established in building markets for the urban and transportation sectors. In 1855, Burnell observed that "almost all of the works executed in water in England at the present day are executed with it [natural cement]."[596] Donaldson's *Handbook of Specifications* from 1859 made

593 Rivington, *Notes*, 158.

594 Cummings, *American Cements*, 213.

595 Cummings, *American Cements,* 213.

596 Burnell, *Rudimentary*, 86.

numerous mentions of the use in urban construction works.[597] The reports of the railroads also demonstrated their consumption of the material. This material ascendancy did have its environmental cost. By the early 1840s, the British Parliament had to address the collapse of one of Great Britain's major harbors due to cement stone mining.

Captain John Washington was put in charge of investigating this troubling occurrence. His identification of the cause and description of the impact was contained in a letter to a colleague. It read as follows:

> It is not for me to say who is to blame for the extreme neglect of this port, but that it has been shamefully neglected during the last 20 years is manifest, and thus the best and only harbour on the east coast of England, between the Thames and the Humber, a harbour in which, in a north-easterly gale, 400 vessels have at one time taken refuge, is now all but ruined for the want of a little timely precaution. It is the business of an engineer to report upon the best steps to take in order to arrest any further deterioration, but the more obvious measures would seem to be to put a stop to the daily practice of carrying away the cement stone from the foot of the cliffs, and to adopt at once a vigorous and well-considercd system of groyning along the shores; had this been done 20 years ago, a Mortella tower, Rainhaam's Battery, and other fortifications on Landguard east beach, long since washed into the sea, might have been saved; a deep watcr-channel into the harbour carrying seven fathoms, where thcrc is now a shingle beach as many feet above high-water mark, would have been preserved; the high and low light would still have been available for navigation in the direction in which they were intended; the whole strength of the flood and ebb streams for scouring the channcls might have been maintained; a shelter from the sea, caused by southerly and south-westerly gales, would have been preserved; the scouring away of the beach on the eastern face of the town would have been avoided; upwards of 40 acres of good ground, excellent pasture land, with tenements and other property, might have been preserved to her Majesty's Government; but, worse than all, in a national point of view, a harbour that a few years since would have afforded shelter in an easterly gale to the largest ship in the North Sea fleet, is now barely available for a frigate.[598]

Through the investigations of the devastation of Harwich Harbor, it was revealed that this once valuable and protected port was now a sacrifice zone for natural cement

597 T.L. Donaldson, *Handbook of Specifications* (London: Achtley & Co. 1859).

598 UK Parliament, *Harbours of Refuge,* 103.

production. Many local observers, including a Captain George attributed "the falling down and the washing away of the Beacon Cliff, commonly called Blackman's Head, the which has been caused and accelerated by the excavating for the cement stone."[599] Government interrogators asked "when did the excavation of the cement-stone commence?—I think about 20 years ago; but they always collected it from the shore before they began to excavate."[600] Another local corroborated the timeline. "How long has this practice been going on?—I have known it for 27 years." The interrogation continued, "Was it so before they began to remove cement-stones?—No; they were removing cement-stones, but not to the same extent that they are now."

Captain Washington concluded from these interviews that "the injury to the harbor has arisen from two causes, viz., the removal of cement-stone from the front of Beacon Hill, and the removal of stone from the cliff at Felixstowe."[601] He estimated that "now, the traffic in cement stone began about the year 1812, or 30 years ago, since which period, I am credibly informed, that upwards of a million tons of stone have been carried away from the shores in question."[602] He specified, "I am credibly informed that since 1812 upwards of a million tons of this stone have been carried away from the shores….Of the large quantities of cement-stone which have been carried away from under Beach cliff (Harwich) I am informed that 200,000 tons have

599 UK Parliament, *Harbours of Refuge*, 104.

600 UK Parliament, *Harbours of Refuge*, 104.

601 UK Parliament, *Harbours of Refuge*, 104.

602 UK Parliament, *Harbours of Refuge*, 209.

been taken away by the Board of Ordnance and applied to government uses."[603] Aside from suggesting that the Ordnance Department ought to be responsible for the damages, mining of natural cement stones persisted.

Redgrave wrote of the persistent demand throughout the 1840s. "We have now reached the period when the railway fever set in, and the demand for cement stone at Harwich became very extensive, indeed the stock of stone threatened to become exhausted," he described.[604] The material was not exhausted as dredgers offered their service to reclaim more of the stones to Washington. A local newspaper documented that, in December of 1846, "the demand for cement stone is now so extensive, caused chiefly by the large quantities of the prepared article used in railway work, that the stock usually consisting of several thousand tons at this season is now quite exhausted, prices have in consequence risen 30 per cent., while the dredgers are reaping a proportionate benefit. The winter promises to pass over without much suffering of the poorer classes…It is calculated that £25,000 per annum are paid away in wages alone to workmen employed in this trade."[605] Recovering stones from land had ended, but, despite the claims of shortages, the dredgers continued to collect the stone. In fact dredgers offered to "dredge to clear the harbor for the stones."[606] Francis records that this practice persisted until 1900.

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603 UK Parliament, *Harbours of Refuge,* 209.

604 Gilbert Redgrave, *Calcareous Cement: Their Nature and Uses* (London: Charles Griffin and Co., 1895), 30.

605 Redgrave, *Calcareous Cement*, 30.

606 UK Parliament, *Harbours of Refuge,* 209.

Although the transition to natural cement happened relatively abruptly in Great Britain, other regions in the western European building regime were slow to adapt. Burnell recorded an early example of this technological diffusion when, in 1802, "cement was produced from the same "septaria" at Boulogne, France, and this was the beginning of the cement industry in that country."[607] Although this provided a supply of natural cement stones to parts of France, many western European regions and countries remained outside of the natural cement development zones. Pasley described this regional variation and associated lithic building alternatives. "Although the limestones which furnish hydraulic limes naturally are very plentifully distributed, circumstances may occur to render their employment too expensive. In such cases their want is supplied, at least upon the continent, by the use either of trass or of puzzolano (either natural or artificial), which are mixed with the rich limes, or by the use of artificial hydraulic limes," he wrote.[608]

The adaptation of natural cement to the British building regime was rapid due to material abundance and the qualities of cement based off of Parker's method. The environmental catastrophe at Harwich demonstrated the cost of overharvesting a particular deposit, but seemingly did not slow the production or use of the material. It did not mark the end of the natural cement industry in Great Britain, or even at Harwich. The ruin of Harwich Harbor resulted from the success of natural cement in building industrial infrastructure, where the railroads created a positive feedback loop of ever increasing production and consumption. All of these changes brought about more intensification of

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607 Richard K. Meade, *Portland Cement: Its Composition, Raw Materials, Manufacture and* Analysis (Easton, PA: The Chemical Publishing Company, 1926), 5.

608 Burnell, *A Rudimentary,* 39.

the industrial mass-production of cement and transformations of industrial urban and transportation networks. By the 1840s, the process of cement development was well underway due once again to local fossil abundance.

Yankee Cement

Perhaps no other builder had a more illustrious career in the United States during the first few decades of the country's existence than Benjamin Henry Latrobe. The British architect and engineer emigrated to America in 1795 and oversaw the construction of various notable buildings including the U.S. Capitol building. Like Smeaton, he remained active until his death in September of 1820. On January 12 of that year, he sent a letter to the president of the newly created Second Bank of the United States outlining a bill for British cement. The former bank president had requested the material be imported from England "in order to make an experiment of its appearance and effect in case any part of the new Bank should be usefully covered with it, he having understood that it is now generally used in England."[609] By the time of Latrobe's letter, a domestic substitute for English natural cement had been discovered in the Appalachian Mountains of New York state. Although it had not been widely disseminated by the building of the Second B.U.S., American natural cement would soon replace the need for imports wherever the material could be accessed. Many historians have proposed explanations for the form of industrial development in the United States, which increased more rapidly in the north.[610] After 1820, access to abundant, durable and hydraulic cement at relatively low costs can

609 Benjamin Henry Latrobe to Langdon Cheves, January 12, 1820, MS2075: W. Lloyd Wright papers; series 1, box 3, folder 15. Special Collections Research Center, George Washington University Libraries, Washington, DC.

610 See: John Majewski, *A House Dividing: Economic Development in Pennsylvania and Virginia Before the Civil War* (Cambridge: Cambridge University Press, 2000).

be added as a factor that helps explain the divergent political economy of the antebellum United States.

Early industrialization in the United States was related directly to canals. In his 1791 "Report on Manufactures," Alexander Hamilton made the direct comparison between the success of canals in Great Britain and their potential for promoting similar developments across the pond. "There is perhaps scarcely any thing, which has been better calculated to assist the manufactures of Great Britain, than the ameliorations of the public roads of that Kingdom, and the great progress which has been of late made in opening canals. Of the former, the United States stand much in need; and for the latter they present uncommon facilities," he wrote.[611] These transportation routes, as Hamilton understood, would spread the dendritic development zones in precisely the same way as they did in Great Britain a generation earlier. Such a national system of canal networks did not emerge until much later. Despite all of the efforts for developing such transportation routes, a mere 120 miles of canals existed in the U.S. by 1820.[612] Thirty years later, 4,258 miles of canals stretched across the rapidly industrializing nation.[613] Historians have provided myriad explanations for the timing and geographical specificity of how Hamilton's vision actually played out.[614] Again, few have considered the materials that many of the large antebellum canals were built with.

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611 "Alexander Hamilton's Final Version of the Report on the Subject of Manufactures, [5 December 1791]," *Founders Online,* National Archives, https://founders.archives.gov/documents/Hamilton/01-10-02-0001-0007. Original source: *The Papers of Alexander Hamilton*, vol. 10, *December 1791–January 1792*, ed. Harold C. Syrett. New York: Columbia University Press, 1966, 230–340.

612 Richard C. Waughe Jr., "Canal Development in Early America," *Canal Age,* vol. 30, 5.

613 Waugh Jr., "Canal," 4.

614 Christopher F. Jones, *Routes of Power* (Cambridge: Harvard University Press, 2014).

During the roughly half-century after the Revolutionary War, large-scale infrastructure projects in the United States were referred to as "internal improvements." Historian John Larson recorded that although the term had multiple meanings, it eventually, "narrowed…until it became synonymous with public works for improved transportation."[615] One of the more ambitious plans for national transportation networks included Albert Gallatin's national survey of "public roads and canals" commissioned by the US Treasury in 1807. Gallatin surveyed four classes of internal improvements, "Great Canals from north to south; communication between Atlantic and western waters; communications between the Atlantic waters and those of the Great Lakes, and the River St Lawrence; and interior canals."[616] Gallatin's report demonstrated the importance of water communications. It was also a response to a relative dearth of such development projects. The lack of national transportation projects was understood by Gallatin as the result of "mistaken local interests." Gallatin explained, "the great demand for capital in the United States and the extent of territory compared to population, are, it is believed, the true causes which prevent new undertakings."[617] The War of 1812 proved another impediment to developing such networks shortly after his report and his plan of national canals never manifested.

Regardless of the failure of Gallatin's plan to materialize, his report offers two significant points related to material availability and development possibilities. First,

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615 John Larson, *Internal Improvement: National Public Works and the Promise of Popular Government in the Early United States* (Chapel Hill: The University of North Carolina Press, 2001), 3.

616 Albert Gallatin, *Report of the Secretary of the Treasury on the subject of Public Roads and Canals,* printing ordered by the US Senate (Washington: R.C. Weightman, 1808), 8.

617 Gallatin, *Report of the Secretary*, 6.

local interests were powerful determinants of what infrastructure projects were pursued and why. Gallatin's national focus was unusual at a time when such projects were typically undertaken by states, corporations or local organizations.[618] Second, the shape of a national system of waterway transportation was much more limited than what emerged after the discovery of cement. Each can be considered in relation to canal construction before and after the discovery of American natural cement. Many historians have noted that Virginia seemed poised to become the industrial center of the United States prior to the 1820s. For this reason, it provides a fitting case study for the state of hydraulic infrastructure prior to the discovery of natural cement in the United States. Historian Sean Adams has pointed out the fossil endowment of Virginia that had rich deposits of high quality bituminous coal.[619] Upon seeing the large deposits of coal in 1796, Latrobe wrote in his diary, "such a mine of Wealth, exists I believe nowhere else! A Rock, a *Mountain* of Coal sunk down 30 feet from the Surface, bored 10 feet more, and yet no substratum found!"[620] These deposits were massive and certainly could provide abundant supplies of mineral energy during the period of the Early Republic.

Adams provides a robust analysis of the government policies, labor regimes and private interests that all prevented the exploitation of these resources on a scale that Pennsylvania did decades later.[621] Material availability also determined the possibilities

618 See: Sean Adams, *Old Dominion Industrial Commonwealth: Coal, Politics, and Economy in Antebellum America* (Baltimore: John Hopkins University Press, 2004).

619 Adams, *Old Dominion*, 2.

620 Benjamin Henry Latrobe, *The Virginia Journals, 1796*-1798, vol. 1, ed. Edward Carter (New Haven: Yale University Press, 1977), 97.

621 Adams, *Old Dominion*, 4.

of moving such coal to markets. As Gallatin's plan demonstrated, without access to abundant, durable and waterproof cement, canal projects were typically modifications of natural waterways. For instance, many of the canals suggested in the report sidestepped rapids or waterfalls on otherwise navigable rivers.[622] The Niagara and Mohawk as well as Ontario canals were the longest proposed canal projects, but remained localized in western New York.[623] They were much smaller than the Erie Canal, which eventually crossed the state. In this age of riparian improvements over the construction of large-scale artificial waterways, development along the James River was an early leader. The James River served as the main form of water transport in Virginia. The first major canal project in what would become the United States was a cut around the "great falls of the James River at Richmond," which was interrupted by the Revolutionary War."[624] This early attempt to modify the James River navigations was inspired by English canals and carried out by English engineers. After the war, this project was extended with a number of Granite and wooden locks that facilitated barge traffic in "the City of Richmond lying 120 miles from the river's mouth in Chesapeake Bay."[625] Other canal developments were built in the state of Virginia along the James River that incorporated "stone locks [that] are beautiful specimens of masonry."[626] The falls of the James River remained a dividing feature of eastern and western Virginia even after bypasses of the falls were created.

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622 Larson, *Internal Improvement,* 60.

623 Larson, *Internal Improvement,* 60.

624 *Encyclopaedia Metropolitana*, vol. 23, 223.

625 *Encyclopaedia Metropolitana*, vol. 23, 223.

626 *Encyclopaedia Metropolitana*, vol. 23, 224.

Since the coalpits of Virginia were west of the falls and not along the river, accessing such materials proved difficult.

Latrobe's trek to the coal mines of the Old Dominion demonstrates the lack of infrastructure reaching the coal mines. Excerpts from his entry on April 19, 1796 described that, "a most wretched bridge leads across the lower falls to Manchester…Its construction is so various, that to describe it is a task more unpleasant if possible than to pass…Manchester is a small decaying town, irregularly built on irregular ground…From Manchester, the Coalpit is 10 miles. The road lies almost entirely through woods in a few places broken by the small opening of a miserably cultivated spot."[627] The bridge pillars were made of stone and timber, hastily thrown together. The city of Manchester remained underdeveloped. Travel to the Coalpit was by road and choked with woods. Finally, the cultivation in this part of the country was not on par to what Latrobe thought fitting. He described a landscape without the development of reliable water communications to move bulk materials.

Such underdevelopment was related to a multiplicity of factors, but also demonstrated the limits of building hydraulic infrastructure without hydraulic cement. American builders often relied on substitutes for calcium carbonate since the colonial period. *The Transactions of the Philosophical Society of London* provided an informative passage from Thomas Glover who described that in colonial Virginia during the late seventeenth century, "the Planters houses are built all along the sides of the Rivers for the convenience of shipping; they build after the English manner, whiting the inside of their houses with mortar, made of burnt oyster shells. Great heaps of which are found here,

627 Latrobe, *The Virginia Journals*, vol. 1, 96-97.

made formerly by the savages, who subsist in part by that fishery."[628] In the colonial period, the discovery of shells of little use to the indigenous people of North America, referred to as 'savages,' provided a supply of a material to apply, similar to the European method of material substitution at the time. The use of shell limes persisted well after the colonial period as the 1841 issue of the *Builder* recorded that "in America, all along the sea-coast no other kind of lime is used, and the shells are in such amazing abundance."[629] Sea shell substitutes sufficed for dry land building.

However, as Smeaton's experiments showed, seashells proved an inadequate substitute for hydraulic building. This was unfortunate for hydraulic builders of Virginia. In Latrobe's description of the young state, he provided a detailed account of an abundance of such materials. Upon finding a geologic layer of seashells along the banks of the James River, Latrobe described that "on the banks of all the great rivers below the falls…are immense and inexhaustible beds of oyster shells….They burn into a very good lime, and are used in all the ironworks to flux the Metal in preference to fresh Shells or Limestone."[630] He continued to explain that, "the banks of Shells are not confined to the borders of the Rivers. Among the Valleys of the Inland, and on the Side of the hills, below their summit are equally astonishing and inexhaustible banks of shells of various kinds…[that burn] to very good Lime in my grate."[631] This abundance of shells was in

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628 Mr. Thomas Glover, "An Account of Virginia, its Situation, Temperature, Productions, Inhabitants, and their Manner of Planting and Ordering Tobacco, &c.," in *Philosophical Transactions of the Royal Society of London* (1676-1678), 635.

629 "Dissertation," 186.

630 Benjamin Henry Latrobe, *The Virginia Journals, 1796*-1798, vol. 2, ed. Edward Carter (New Haven: Yale University Press, 1977), 408.

631 Latrobe, *The Virginia Journals,* vol. 2, 409.

contrast to a dearth in calcium carbonate deposits. Upon testing various geological strata, Latrobe did find such deposits, but "previous to this discovery it was not supposed that the smallest particle of Limestone was to be found."[632] For reasons unknown, the material was not exploited in any significant cement works. This could have resulted from the impure nature of that deposit as only some of the deposit could be converted to cement. It could also have resulted from the lack of a need for exploiting such resources due to seashell substitutes used in non-hydraulic mortars and plasters. Regardless of the reason, Virginia never developed the materials necessary for monumental hydraulic works.

An example of the poor state of canal building in Virginia can be seen with the James River and Kanawha Canal, started in 1785. Although publicly funded, it remained incomplete by the mid-nineteenth century, a time when railroads proved more efficient for moving bulk goods and the Civil War terminated focus on the project.[633] Prior to the discovery of an abundant, durable and hydraulic cement in the United States, builders worked with the landscape rather than against it. The early builders of canals in the James River dealt with material as well as environmental and cultural limits. The development of canal works along the James River were interrupted by the War of 1812 and abandoned shortly after. Connecting eastern Virginia to the western hinterlands was abandoned until 1835 when Benjamin Wright, of Erie canal fame and a man familiar with the use of American natural cement projects, was brought in to complete it.[634] By this

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632 Latrobe, *The Virginia Journals*, vol. 2, 411.

633 Langhorne Gibson, Jr, *Cabell's Canal: The Story of the James River and Kanawha* (Richmond: The Commodore Press, 2000), 262.

634 Gibson Jr., *Cabell's Canal*, 134.

time, however, railroads were proving to be more economical transportation routes in the industrializing nation. There is no way to tell if the Virginia canal communications would have developed pathways for the coal resources of the backcountry had natural cement, or viable substitutes been available. What is clear is that after the discovery of natural cement, large-scale canal projects expanded significantly across the industrializing north.

That did not keep American canal boosters from dreaming. The New York state legislature passed a bill to begin preparations for building the canal in 1816, before the discovery of natural cement in the United States.[635] The goal of a canal crossing the state of New York was to connect the Atlantic Ocean and Great Lakes. "The commerce of the ocean, and the trade of the lakes," trumpeted the canal commissioners, "passing through one channel, supplying the wants, increasing the wealth, and reciprocating the benefits of each great section of the empire."[636] Despite the grand visions of the promoters of the Erie canal, its early phase of construction demonstrated the limits to building such a monumental project without a robust cement regime. Engineer Benjamin Wright wrote of these uncertain years of the canal's construction. He explained that "the canal commissioners made no provision for the importation of cement. They appeared to think, that common quick lime would do for the work, although I suggested to them, in writing, in 1818, the propriety of making provision for the cement either by importing Trass or Roman cement."[637] The fault of using local limes for hydraulic construction was soon

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635 Harley Mckee, "Canvass White and Natural Cement, 1818-1834," *Journal of the Society of Architectural Historians* 20, no. 4 (Dec. 1961): 194.

636 *Laws*, vol. 1, 140.

637 *Laws of the State of New York, in Relation to the Erie and Chamberlain Canals,* vol. 2 (Albany, 1825), 217.

evident as Wright continued, "where common lime has been used, it gives evidence of soon failing."[638] Importing cement and *trass* was possible, but, as the canal commissioners loathed, there was a high cost to do so. Prior to the discovery of natural cement in North America, the supply of materials for large-scale hydraulic building proved inhibitive.

Although supported by the State of New York under Governor DeWitt Clinton, the engineers in charge of the project, including Benjamin Wright and his assistant Canvass White, knew that they did not have the expertise or the proper materials for such a project. In order to investigate state of the art canal building technology, Canvass White journeyed to England in 1817 and surveyed the British canal network. Legend has it that White "travelled more than 2,000 miles of English canals on foot, examining their construction."[639] This could have been possible as that was roughly half of the inland navigation mileage at the time, although it is unlikely.[640] What is clear is that White's trip demonstrated a process of technological diffusion where the techniques and methods of British canal builders were absorbed with the intent of recreating such systems in the United States.[641] White would have not only observed the locks, aqueducts, bridges and tunnels, but also their construction with natural cement. Upon his return, he knew what materials to look for, just not where they could be found.

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638 *Laws*, vol. 2, 217.

639 Mckee, "Canvass," 195.

640 Hadfield, *Canal Age,* Appendix 1.

641 For a more detailed discussion of this process see: Hughes, *Networks of Power*, 47-79.

The transformative discovery came in 1819. While experiencing difficult dredging in January of 1819, a report to the canal commissioners noted, the discovery that "the stone is all, either gypsum, common lime-stone, or a kind of meagre lime-stone. Of the last, we expect to make a very important use; as, by a number of small experiments, in which, after being thoroughly burnt and slaked, or ground, and mixed in equal portions with sand, it appears to form a cement that uniformly hardens under water."[642] Knowing of the value of impure limestone, White carried out experiments on the material. He discovered that these deposits served as a natural cement stone and he was awarded a patent for the material that was used extensively on the locks of the Erie Canal. Wright said of his colleague, "I have no hesitation in saying, that the discovery of hydraulic cement by Mr. White, has been of incalculable benefit to the State."[643] The canal commissioners wrote of "the waterproof lime, which has been used, during the past season, for the most of the mason work done on the canal, has contributed to swell our disbursements beyond our original estimates…and it will doubtless hereafter be considered as an article of prime necessity, throughout our country, for all hydraulic masonry."[644] White soon sold the patent to the State of New York, leaving natural cement production open for other manufacturers.

Early tests on the material also claimed that cement made from this material were stronger than their European counterparts. In perhaps the first systematic study of American natural cements in 1838, Colonel J.G. Totten wrote that the "tenacity, as

642 *Laws*, vol. 1, 406.

643 *Laws*, vol. 2, 99.

644 *Laws*, vol. 2, 99.

expressed by the number of pounds required to tear open a joint," of American natural cement was at least twice that of Roman cement imported from England.[645] The strength may have been diminished in the cement shipped across the sea, but Totten clearly proved the strength of the American natural cement mortar. Following the discovery of the canal dredgers in 1819, the abundant domestic supplies of natural cement were applied to support a thriving natural cement industry around the mountain deposits of the Appalachian Range.

As the message from the canal commissioners demonstrated, the discovery dramatically changed the possibilities of building in the Unites States. Civil Engineer H.S. Dexter's report to the US Senate in 1840 described the importance of the discovery as "heretofore the principal ingredients of hydraulic mortar were procured at a great expense from abroad the construction of locks; but a species of limestone has been found, dispersed over the whole country, admirably adapted for water cement, and entirely superseding the necessity of foreign supply."[646] The material did change the possibilities of building in the United States, but was not dispersed "over the whole country." In describing the US natural cement deposits in 1863 as part of a War Department Survey, Q. A. Gillmore observed that "the most extensive beds have thus far been discovered in the valleys of the great Appalachian chain of mountains, as they traverse the States of New York, New Jersey, Pennsylvania, Virginia, Tennessee, and the northern portions of

645 J.G. Totten "Brief Observations on Common Mortars, Hydraulic Mortars and Concrete," 1838, 229. http://www.naturalcement.org/Totten-1838sm.pdf.

646 *Laws*, vol. 2, 99.

Georgia and Alabama."[647] By the time Gillmore was writing in 1863, only one cement mill had been established in the deep south. Even though natural cement stone was not found across the whole county, the deposits in the United States were much more expansive than those in Great Britain.

The centers of most intensive canal building were clustered around such deposits. There was a direct relation between these manufacturing zones and the antebellum US canal system. Cement manufacturing and canal growth correlated closely. Around 25,000 barrels of natural cement were produced per year in the 1820s to 1,100,000 barrels a year in the 1850s. In this same stretch of time, canal mileage increased from around 120 to 4,258.[648] Many of the cement mills were also created for such purposes. In documenting the creation of cement plants and why, industrial Historian Robert Lesley listed the following connections between early cement mill development and related construction projects: 1824 Williamsville, N.Y.: Erie Canal; Kensington Conn.: Miscellaneous; 1828 Rosendale, N.Y.: Delaware and Hudson Canal; 1829 Louisville, Ky.: Louisville and Portland Canal; 1831 Williamsport, Pa.: Muney and Lock Haven Canal; 1836 Cumberland, Md.: Miscellaneous; 1837 Round Top Md.: Chesapeake and Ohio Canal; 1838 Utica, Ill.: Illinois and Michigan Canal; 1839 Akron, N.Y.: Miscellaneous; Balcony Falls, Va.: Miscellaneous; 1850 Siegfrieds Bridge, Pa.: Easton and Mauch Chunk Canal."[649] As is shown by this list, many of the early natural cement manufactories were created for the purpose of building canals. Once built, the material could be sent

647 Q. A. Gillmore, *Practical Treatise on Hydraulic Cements and Mortars* (New York: D. Van Strand, 1864), 16.

648 Waugh Jr., "Canal." 4.

649 Lesley, *History of Portland Cement*, 32.

throughout the dendritic development networks of the industrializing United States. The majority of cement production and canal development occurred around the northern deposits. Material availability could be added as an explanation of why canal development, and thus early industrial production, occurred in across the northern antebellum United States. This is not the only explanation, but the development of these artificial waterways differed greatly than those conceived and built before the development of a domestic natural cement industry.

In a conversation with George Washington at Mount Vernon, the President of the United States opined that rather than gold or silver, he "heartily wished for his country that it might contain no mines, 'but such as the plough could reach,' excepting only coal and iron"[650] Latrobe and Washington overlooked another significant resource of industrial development: cement. Had materials been prioritized and deposits of calcium carbonate deposits been available, Virginia, over Pennsylvania or New York, may have become an ascendant industrial center during the antebellum period. Instead, it was the northern states that developed the infrastructure necessary for early industrial development. What Gallatin had imagined in 1808 and what emerged by the mid-nineteenth century differed greatly. Rather than small-scale projects, along natural waterways that connected the north and south, a system of large-scale artificial waterways connected the industrial northeast to the old northwest after 1820. This was facilitated by the mass production of durable and hydraulic cement. Fortunately for the canal builders, most of those canals crossed the natural cement deposits of the northern Appalachian Mountains. The national canal system that emerged spread the dendritic

650 Latrobe, *The Virginia Journals*, 168.

development zone throughout the Ohio River Valley and the Great Lakes region. It far exceeded Hamilton's dream of recreating the British canal system. This instance of technology transfer brought the industrial northern United States into the Second Stone Age.

Conclusion

The natural cement transition transformed building possibilities in the early nineteenth century. From its first discovery along the shorelines of southeast England, it was paired with mineral fuels to create an abundant material that was free from the ancient cement production methods. Ironically named "Roman cement," it differed greatly from its ancient ancestor. Natural cement was fast setting, durable and waterproof. The abundance and attributes allowed for a scaling up of building that transformed the possibilities of industrial development. No longer requiring trass or pozzolan, the material was also free from the constraints of the western European building regime. Although it occurred a generation later, the transformation of the northern United States demonstrated the diffusion of a technology that far exceeded the dreams of the early advocates of internal improvements. By the mid-nineteenth century, natural cement was being extensively used to alter the environments wherever it was applied. Portland cement would soon replace this material, but even this transition was built on the infrastructure that natural cement created. This was the start of a process of development based on the use of massive amounts of anthropogenic stone to promote industrial development that has since spread worldwide and shows little signs of slowing.

CHAPTER SIX

CONCLUSION

Sustaining the Second Stone Age

In the early 2000s, Geologist James Underwood proposed classifying manufactured stones as a fourth geological rock type.[651] Such a proposition has been largely disregarded by the scientific establishment. Despite its rejection as a concept in the field of Geology, this dissertation is inspired by such a claim as anthropic stones now form a noticeable stratigraphic layer on the earth's crust. In order to consider the origins of this concrete cornucopia, this dissertation considered the origins of the contemporary concrete lock-in that now shapes the geographic possibilities of much of the planet. It could be imagined as a sort of historical excavation that cuts through different deposits of anthropic stones—with plenty of sand in between. Layers of such manufactured stones appeared in abundance when large-scale building demand overlapped with the material availability and technology necessary for the sustained mass production of cement. Exploring how those layers formed and why outlines the origins of the most recent Stone Age.

By the mid-nineteenth century, portland cement—a mixture of calcium carbonate and sand fired at extremely high temperatures—had emerged as a yet another cement substitute. In fact, three types of cement were presented as examples of cutting edge technology at the Great Exhibit of the Works of Industry of All Nations held in London

651 In a short article published as a "technical note," geologist James Underwood proposed adding anthropic rocks, rocks altered, moved, or shaped by humans, to the classifications of metamorphic, igneous, and sedentary rock as part of the earth's rock cycle. Mocked by editors for its "philosophical tone" and questioned if the article would not be "better suited for an anthropology journal," Underwood was ahead of his time. J.R. Underwood, "Anthropic Rocks as Part of a Fourth Basic Class." *Environmental and Engineering Geoscience* 7 (February 2001), 104-110.

in 1851.[652] These included hydraulic lime, natural cement and portland cement. This was the past, present and future of building with anthropogenic stones. In the half-century after this showing, portland cement had become a leading material in building with manufactured stones. By the start of the twentieth century, the portland cement industry had reached technological momentum with the advent of the rotary kiln that could continuously produce cement in great volumes and could be fired with any fossil fuel type. These systems soon spread wherever the abundant raw materials of calcium carbonate, sand and fossil fuels could be found. Large-scale building with cement spread as well. This was the final cement transition in the millennia long path to the current concrete moment.

The origin story of portland cement demonstrates the material's role in sustaining the mass production and use of anthropic stones. Its invention occurred along the Thames River in the energy rich environments of Parker's experiments. Debate persists around whether or not Joseph Aspdin was the originator of portland cement, due to the title of his 1924 patent.[653] Regardless of who invented the contemporary bonding agent, his son was engaged in its manufacture in London by mid-century.[654] There is also debate over what drove development of this alternative to the natural cement that was used extensively across the island. Many have argued that the switch from natural cement to artificial cement in Great Britain at mid-century was due to the depletion of natural cement stones. Portland cement boosters often repeat that origin myth. For instance, a pamphlet from

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652 *Official Descriptive and Illustrated Catalogue of the Great Exhibit of the Works of Industry of All Nations,* (London, 1851).

653 Francis, *Cement Industry,* 16.

654 Francis, *Cement Industry,* 110-130.

William Aspdin, argued that his alternative to natural cement stones demonstrated a material that could be produced in abundance and prevented a tax on them by Sir Robert Peel.[655] Research for this dissertation could not corroborate this story with evidence. However, the collapse of Harwich Harbor proved the environmental costs of overexploiting one deposit as is required with natural cement production. Additionally, as a survey of the economic history of Great Britain by J.R. Claphman noted, at a time of liberalizing trade laws, the British government "left export duties on wools and skins, china clay and 'cement stone.'"[656] This demonstrated a willingness to protect the natural cement stones, which proved unnecessary after the portland cement transition.

Many have suggested that the success of the portland cement industry was due to improvements related to its production and the material's strength. Another factor is related to the ability to mass produce anthropic stones due to being free from the organic economy. The method pioneered by lime burners and brick layers of London centuries ago has since grown to megalithic proportions. This system has created building material abundance, but questions remain surrounding if humanity's reliance on such a material is sustainable. John Evelyn first grappled with the possibilities and limits of such materials. His critique of the air pollution from lime kilns that burned calcium carbonate and coal appeared in a pamphlet dedicated to promoting silviculture in 1670 demonstrated this central tension.[657] On one hand, producing cement in the mineral economy provided a building material with a greatly diminished demand for timber as firewood or building

655 Francis, *Cement Industry*, 123.

656 J. H. Clapham, *An Economic History of Modern Britain: The Early Railway Age, 1820-1850* (Cambridge: Cambridge University Press, 1939), 498.

657 Evelyn, *Sylva*.

supplies. On the other, it polluted the air. This cost of burning fossil materials with fossil fuels has grown to megalithic proportions as the mass production of cement is now a major contributor to greenhouse gas emissions. Concrete made with portland cement may very well prove to be the building material with the least impact on the biological world, but its production will continue to contribute significant amounts of greenhouse gas emissions to the atmosphere.

Another relevant consideration of building with anthropic stones that is revealed in the deep history of the material is that structures built with the material are not permanent. Roman pozzolan cements showed the greatest longevity as some structures still stand. They will fall someday. Those built with pozzolan cements in early modern Europe showed signs of significant decay in roughly a century. In his 1840 survey, Dexter wrote of "the failure of many of their [European] locks, aqueducts, and other important structures, which, though of recent origin, exhibited all the characteristics of age without the possibility of attributing these unexpected dilapidations to any other cause, than the bad quality of the mortar, or cement made use of."[658] Natural cement structures proved more durable, but also eventually decay. Reinforced concrete structures made of portland cement may have the shortest lifespan. Since many of the structures that were built in the twentieth century will reach their life expectancy in the twenty-first, more and more cement will be needed to repair them or catastrophic collapse of buildings and infrastructure will persist. Sustaining the portland cement regime will be essential for maintaining the structures that shape the world today.

658 Dexter, "Observations," 15.

This dependence demonstrates the technological lock-in that building with anthropic stones has brought. Wherever cement is used to radically alter the possibilities of human geography, it also shapes the societies where these transformations occur. Nothing demonstrates this more than the hydraulic cement building regime of Great Britain at the end of the eighteenth century. Smeaton's mixtures pushed the ancient pozzolan cement regime to new heights. Fossil cement paired with pozzolan provided a durable and relatively abundant material. It was used to make hydraulic infrastructure that included canals and ports, each related to the drivers of industrial take-off. These applications conditioned the lives of those in the colonies that were tied to the metropole, the countryside where canals stretched and in the port cities where materials were accumulated. Natural cement intensified each of these processes through its liberal application in large-scale projects that created the first industrial society. It also set the path for the lithic development that would follow. For better or worse, the actions of people around the world are still shaped by the development model created from iron, coal and cement.

Considering how humanity arrived in the modern lithic epoch will help inform the decisions about its future. In order to understand the current moment, one must step back and explore the *long durée* of the production and use of anthropic stones. The Roman cement regime paired the material and cultural factors that guided builders in western Europe for two millennia. It also demonstrated the limits that persisted in relation to the mass production of cement in an organic economy. During the thirteenth century, the British freed cement production from those limits and began the period of mineral cement production. Although it took five centuries, once the discovery of a material substitute for volcanic sands was found and the cultural requirements for cement transitions were met, the scale of production and application expanded dramatically. Wherever natural cement could be found, modern industrial development could follow. Portland cement further liberated these zones from natural cement deposits while scaling up the amount of cement that can be produced. This has since sustained the major concrete systems that exist around the world today. Throughout this history, production of abundant amounts of cement and concrete resulted from the cultural and material factors that shaped its adoption and to what end it is used. It demonstrates the roots of humanity's contemporary relationship to Stone Age technology.

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