Brick by Brick: Civil Engineering and Modern Alternatives to Traditional Concrete

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia ● Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Ethan Ames

Spring 2024

On my honor as a student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Caitlyn D. Wylie, Department of Engineering and Society

Introduction:

Civil engineers are responsible for determining which materials are used in the structural framework of a construction project. In most cases, some combination of concrete and steel will be used for a modern development, though other materials may be used according to the specific needs of a given development. While these unique demands are typically caused by environmental conditions, such as soil or climate, they may also be associated with other factors, such as financial or community needs. Civil engineers have a unique position in terms of their ability to shape the impacts of large infrastructure projects. Design engineers, for instance, are capable of significantly reducing the carbon emissions of their developments through material selection, though there are a number of obstacles in doing so. These barriers ensure the continued use of materials which are neither sustainable nor environmentally friendly, perpetuating processes which will have negative long term impacts on the world. Concrete, one of the most commonly used construction materials in the world, is responsible for roughly 8% of human carbon dioxide emissions, with 0.9 pounds of carbon dioxide emitted into the atmosphere for every pound of cement sourced from the natural environment. This provides us with the premise of an important question: in cases where the financial interests of a client and environmental interests of project stakeholders are in conflict, how should an engineer respond? Investigation of this topic will involve an assessment of traditional construction materials, establishment of a framework by which the environmental impacts of building materials may be assessed, and research into strategies and technologies that may best meet the demands of both client and community. By applying the frameworks of environmental conservationism and stakeholder theory, engineers may rethink modern construction practices to mitigate the harmful environmental impacts of traditional methods and materials.

Background:

Concrete is used as a principal material in virtually every major construction project in the developed world. This is due to its high compressive strength, which allows it to support heavy loads, as well as its natural ability to withstand the elements (Nevill, 2011, p. 952). Concrete grows progressively stronger over time as a result of its unique curing process, it can easily be shaped to the contours of a mold for a number of given applications, and may be augmented in its various structural properties through additives to its mixture or through structural elements such as rebar being added to its solid form. Concrete is a singularly versatile and practical material, capable of carrying structural loads in a number of conditions, and is therefore essential. However, concrete is also notoriously harmful to the environment, being responsible for approximately 8% of anthropogenic carbon dioxide emissions on an annual basis (Lehne, 2018, p. 7). Because of the scale of concrete's negative environmental effects, this will be the primary material focused on in this investigation.

In order to understand concrete's role in structural design, one must have a working definition of what concrete actually is. Concrete consists of two primary materials: aggregate and cement. Aggregate is a collection of granular materials, like gravel, which is mainly responsible for determining the concrete's material strength. Cement is a binding agent which, when mixed with water, forms a cohesive solid which holds the coarse aggregate together. Both of these components are essential to the formation of concrete, and have significant detrimental effects on the environment. Other admixtures, such as superplasticizers or retardants, may be added to concrete to enhance or alter its material characteristics. Rebar, mesh, and other physical additives are commonly used in concrete to improve its structural properties. These additive structures and substances are sourced to some degree from natural materials, and therefore have a proportional environmental impact, though they will not be covered extensively in this study.

The materials that make up concrete are sourced from the natural environment, usually through non-sustainable means. Coarse aggregate is typically mined from crushed or broken up rock, and shipped to site for mixing. This process, both in mining and transportation, releases large amounts of carbon dioxide into the atmosphere, mainly from the machines used to break down and ship the rocks. There are also concerns regarding how much aggregate can be sourced from a certain location before local ecosystems are affected (McNeil, 2013). Cement also plays a major role in determining the extent of a batch of concrete's environmental impact, with 0.9 lbs of carbon dioxide emitted for every pound of cement manufactured (Portland Cement Association, n.d., p. 2). Transportation also remains as an impactful source of carbon dioxide emissions, given the relatively limited number of locations from which rock and lime may be sourced for use in producing the raw elements of concrete, and the wide demand for these materials across the country.

In spite of these drawbacks, concrete remains to be an industry standard when it comes to material selection in major construction projects. Concrete is relatively cheap to acquire in bulk, and exhibits an impressive ability to resist compressive force. When paired with internalized rebar, concrete may also perform well under tension, making it a fairly versatile material. Concrete is highly resistant to fire, and can last for long periods of time in the elements without losing its structural integrity; it is also easy to mold and can therefore be used in a wide variety of applications (Nevill, 2011).

In addition to any technical reasons one can identify, many social systems are in place which maintain the status of concrete as a primary construction material. If concrete is mishandled during the construction process, or improperly attended to after construction is complete, material failure may occur, leading to devastating consequences. For this reason, many government regulations have been set in place for concrete based construction projects, which act as quality control measures (Gjorv, 2011). Because concrete is so common, these regulations are fairly straightforward and are therefore easy for engineers and construction workers to comply with. The same cannot be said on remotely the same scale for any alternative building material that may be implemented as a sustainable counterpart to concrete. The environmental significance of concrete usage as a social issue immediately comes up against the social value of public safety. If concrete is the best available building material not only in terms of cost, but in terms of safe implementation and use, then there are two different social values that must be taken into consideration before reducing or altering the prevalence of concrete's use in the modern construction industry.

Another social structure maintaining the status of concrete as an industry standard is found in the organization of most engineering firms. Structural engineers and architects are generally considered to be responsible for the selection of materials used in a given project; however, these parties are beholden to their employers and clients in any decisions they make. The concerns of these parties are often financial, and pressure engineers to develop designs which are risk averse and therefore less likely to lose money. Construction schedules may face significant delays as plans await approval, and clients may become concerned by potential cost and liability issues stemming from use of alternative construction materials (United States Environmental Protection Agency, 2023).

Civil engineers are therefore faced with heavy pressure to utilize concrete in their designs, especially for larger developments bearing heavier loads. Technical, financial, and social pressures each indicate that concrete is an ideal material for use in major projects, despite the known environmental drawbacks of its usage. This all makes sense on the surface, though it begs the question – who is going to bring about the shift away from concrete towards sustainable materials if not the design engineers whose creations are responsible for the enormous demand for concrete we see today? Do engineers have a greater responsibility to the public for the environmental impact of their creations, or to their clients and their financial concerns? How do other factors, such as public safety, come into play? The issue of concrete's usage in construction can only be addressed through exploring these questions.

Social Frameworks:

Over the course of the twentieth century, the public conscience became increasingly aware of the impact industrial technology has had on the environment (Pepper, 2019, p. 11). Climate change, mass pollution, deforestation, and poor waste management practices all became the subjects of heated debate throughout the last century, with many groups and individuals voicing their concerns over how human activity is detrimentally affecting the environment on a massive scale. The effects of climate change, for instance, have the potential to put entire ecosystems, populations, and infrastructure systems in jeopardy over the coming decades. Environmentalists claim that current environmental practices are unsustainable, and will eventually have cataclysmic effects on human society.

It wasn't until the 1960s that environmentalism began to build traction as a social movement in America. Tragedies like the Love Canal incident, where improper disposal of hazardous waste resulted in an epidemic of physical defects and stillborn births in a small town community, revealed the critical importance of monitoring the environmental impacts of human behavior (Scheffer, 2013). Whether environmentalist concerns are driven by self interest (Pepper, 2019, p. 3), altruism, or even a pure respect of nature (Scheffer, 2013), it is clear that environmentalism has emerged in recent years as an influential cultural and political force.

Stakeholder Theory states that businesses and other firms are responsible not only for the interests of their shareholders, but for the groups and individuals who are affected by their activities (Gibson, 2000, p.1). These groups are referred to as stakeholders. This model affects the decision making process of the firm, forcing those who adopt it to weigh the interests of multiple parties, often seen in conflicts between financial and social interests (Gibson, 2000, p. 1). Stakeholder theory is key in making an environmentalist analysis of today's construction practices, providing researchers with a framework by which the activities of large corporations can be appraised. Firms whose activities have a negative impact on the environment are beholden to the members of communities who are directly impacted by those actions. Love Canal is a good case study for this: a corporation, guided purely by financial interests, neglected to properly dispose of the hazardous waste generated by its industrial practices. Failure to take into account the interests of stakeholders, the people whose homes would be eventually built on the same plot of land which was used for the waste disposal, resulted in loss of life and injury across an entire community (Fjelland, 2020, p. 1). Stakeholder theory is a credible framework to analyze the activity and impacts of firms, and allows environmentalists to hold developers accountable for the ecological effects of their work.

Some critics argue against Stakeholder Theory by claiming that a firm's only responsibility is to deliver profit to its shareholders. Firms are free to pursue social agendas and engage in various activities to benefit the communities they serve, but these are secondary to their main objective of making money for the people who have taken a risk by investing capital in the organization. While this is a fundamentally sound claim in terms of free market economics, it also alleviates firms of all accountability for the impact of their operations. This leads to a severe power imbalance considering the relative power major corporations hold compared to the communities they serve and who are affected by their operations. Shareholder Theory, as opposed to Stakeholder Theory, provides no system for managing the ethical responsibilities of corporations. Shareholder Theory takes into account the role of a firm in society as a whole, including its role in the natural environment, and directs the action of the firm accordingly.

The construction industry, specifically in regards to their material selection norms for the purposes of this study, are rampant with practices which have immense negative effects on the environment. Environmentalists claim that nature should be protected from human activity, and hold concerns regarding the harm which may befall various communities should current industrial practices go unchecked. Through stakeholder theory, it is possible to connect environmentalist concerns to a responsibility of construction firms to manage the environmental outcomes of the choices they make. Firms must negotiate between the environmentalist concerns of their stakeholders and the financial concerns of their shareholders, striking a balance between the two. A number of philosophies exist in terms of how to address this balance, with two of the most commonly accepted being environmental conservationism and environmental preservationism.

As a philosophy, Environmental Conservationism may be described as the idea that the materials we source from the environment ought to be obtained in a way that ensures their continued availability and maintains an ecological balance (Rome, 2003, p. 1). Material should be acquired through sustainable means and without risk of pollution in the environment.

Conservationism is a useful practice for construction engineers, who rely on natural resources for virtually every project they work on. Environmental Preservationists, on the other hand, believe in absolute non-interference between humans and nature (Rome, 2003, 1, 3). This theory is almost never practiced on a wide scale, given society's widespread reliance on natural resources, though it may be exemplified on a local level through the National Park System. Environmental Preservationism typically serves to function more as an ideal than a practical suggestion, embodying the respect towards nature that many environmentalists hold as a core belief. Preservationism and Conservationism have some overlap, but are typically distinct in terms of their application as an analytical framework. Conservationists strike a balance between human needs and what they consider to be an ethical obligation to protect nature (Rome, 2003, p. 1, 3).

Environmental preservationists may argue that the only way to effectively reverse humanity's negative impact on the environment is to completely divest from use of natural resources for industrial purposes. This action would be virtually impossible, as society would no longer be able to function on any level without our continued use of industries reliant on natural resources. The framework of environmental conservationism is more useful than environmental preservationism for this investigation, as it doesn't fully prohibit engineers from meeting the needs of their client, while simultaneously demanding that engineers protect community stakeholders in regard to the environmental impact of their developments.

Assuming that the conservationists are correct that humanity has both a duty to protect the natural world and the ability to do so while acquiring the materials necessary for society to function, then civil engineers are not exempt from this duty. In fact, engineers may have the most power of any discipline to strike a balance between the human and natural elements at play here. In the analysis of material selection for use in construction projects, concrete fails to meet the standards of sustainability and cleanliness that Environmental Conservationism demands.

The challenge then becomes to develop a material which fills the role of concrete in a structural system, while keeping costs low and minimizing carbon dioxide emissions. Aggregate conservation, concrete recycling, and reduction in material use are all viable strategies to reduce the carbon footprint of practices associated with the use of concrete. From a materials selection perspective, however, there are a number of alternatives to standard concrete which may also improve the sustainability of common construction practices in the present day. While both of these approaches are useful for meeting environmentalist goals in a construction context, alternative materials for structural concrete are often neglected in current discussions regarding environmentalism in civil engineering fields. In spite of this, there has been a tremendous amount of progress made in this field in recent years, much of which shows promise as a potential industry standard as research continues.

Alternative Materials:

A number of materials and technologies are being developed to reduce the environmental impact of concrete, such as rammed earth. Rammed earth bricks are created from densely packed dirt. Soil is hydrated, compacted, and left to cure until it reaches its design strength. Rammed earth is often mixed with trace quantities of cement, which provides it with increased strength and resilience to the elements, such as rainfall. This material, cement stabilized rammed earth (CSRE) shows immense promise as an eco-friendly building material (Kariyawasam, 2016). Rammed earth bricks behave well in compression, meaning they can support heavy loads, but fail under tension, both of which are properties they share with concrete.

Rammed earth bricks are not yet widely used as a construction material due to their diminished strength compared to concrete. They also take more man-hours to assemble, and are therefore more expensive to produce than a simple concrete mix (Greenspec, 2020). However, rammed earth is known to have significantly less environmental impact than concrete. CSRE is still a developing technology, and stronger rammed earth mixes are being developed. Rammed earth cuts out the carbon dioxide emissions created in mining and crushing aggregate, and doesn't need to be transported long distances due to the ready availability of soil (Ciancio, 2013, p. 4). They are also responsible for less off-gassing of chemical contaminants than concrete, which has immense health benefits for the occupants of buildings built out of rammed earth (Keefe, 2005).

Rammed earth also has a historical precedent, as people have long built out of rammed earth in one form or another. In the United Kingdoms, for instance, rammed earth practices have a nearly 200 year history (Maniatidis, 2003, p. 1). Rammed earth is still used in many parts of the world, especially in the developing world, where access to industrial construction technology is not reliable (Maniatidis, 2003, p. 10). For this reason, much of the skepticism that an alternative building material might receive from contractors and government regulators would not fall as heavily on a rammed earth structure.

Critics of rammed earth may point out its numerous weaknesses in comparison to concrete. Rammed earth is not able to support the same heavy loads as concrete, meaning that it will likely never be used in skyscrapers, dams, or other such buildings. Rammed earth is also less versatile than concrete. Rammed earth typically is manufactured into bricks for construction purposes, and cannot be poured into a mold of any shape in the same manner as concrete. Rammed earth is a fairly niche material, though in time it will likely find its place in the construction industry for use in residences, roads, and retaining walls. This reduction in the use of concrete would be significant for anthropogenic carbon dioxide emissions.

Carbon net-zero concrete may be another possible alternative to existing concrete mixes. Carbon net-zero concrete is infamously much more expensive than conventional concrete (Slanger, 2022). However, this cost may be reduced as the technology needed to produce carbon net-zero concrete becomes increasingly widespread. Carbon-net zero concrete maintains the material properties of concrete while being ecologically friendly, and receives significantly less skepticism from regulators and stakeholders than other alternatives to traditional concrete.

For the purposes of this research, we will treat Civil Engineers as environmental conservationists, intentionally minimizing the ecological impact of their projects throughout the development process of each project they undertake. If this is so, then eco-friendly materials such as CSRE or carbon net-neutral concrete should quickly become the industry standard. They cause significantly less harm to the environment than traditional construction materials, while serving the same function.

If engineers behaved as independent actors in creating a building design, integrating these sustainable materials into new designs could happen very easily. However, engineers are much more likely to be acting on behalf of a larger firm, representing a paying client. This inhibits their autonomy, limiting their ability to make decisions which may cost the client more money than necessary. Deviation from tried and true construction methods would be virtually impossible if systems, such as the LEED Certification, weren't in place to encourage developers to create sustainable designs.

LEED (Leadership in Environmental and Energy Design) Certifications are awarded to buildings which exhibit exemplary commitment to sustainability in their designs (Kubba, 2009).

The US Green Building Council awards points based on a variety of criteria across a site design, and delivers a rating of Certified, Silver, Gold, or Platinum to buildings which qualify. While these awards aren't associated with any direct monetary benefit, it becomes a powerful marketing tool for all parties involved in a project. LEED Certifications are highly sought after, and have been proven to encourage designers to pursue environmental conservationist practices. Additionally, other policies, such as government subsidies for LEED Certified buildings, may further extend the feasibility of ecologically friendly replacements for standard concrete in modern construction projects.

Civil engineers are among the most powerful voices for widespread change in construction materials, given that their technical expertise and proximity to infrastructure projects grant them a unique vantage point. Engineers have a responsibility both to the environment and to their client, and have the ability to create innovative designs which meet the needs of both parties. Acting as environmental conservationists may encourage engineers to develop new sustainable technologies for use as construction materials, replacing the materials which are currently considered to be the standard. Engineers' work gives them a role in society that is not purely technical, but also gives them room to impact their community and the environment while meeting the needs of their client.

Conclusion:

Concrete is an essential material in current construction practices, despite being extremely harmful to the environment. Environmental conservationism is a framework which compels developers to source materials in a way which will maintain the ecological balance, targeting pollution and ecological devastation related to overreliance on certain natural resources. Construction materials exist which comply with the framework of environmental conservationism, such as rammed earth and net zero concrete. However, these materials won't be able to replace concrete entirely, at least in the short term. It will allow us to reduce our reliance on conventional concrete, and with improvement in these materials over time the use of these materials may become more widespread.

References in APA format:

Ciancio, D., & Beckett, C. (2013). *Rammed Earth: An Overview of a Sustainable Construction Material*. Third International Conference on Sustainable Construction Materials and Technologies. http://www.claisse.info/2013%20papers/data/e053.pdf

Fjelland, R. (2020, January 27). *When Laypeople Are Right and Experts are Wrong: Lessons from Love Canal*. Bergen Open Research Archive. https://bora.uib.no/bora-xmlui/handle/1956/21698

Gibson, K. (2000). *The Moral Basis of Stakeholder Theory*. JSTOR. https://www.jstor.org/stable/25074344?casa_token=5pwBEJas-XsAAAAA%3AqZG3b4eqKjoGvDr7sQrVteD1fX4p3iPGEe33Ic6-zvtwIfC3iZ7hheZX8Rs9H0Cotf9mz4afhMRjvbbYGZ8QbMQfVkrjf0o0NeRdyzjW4VewqW5C-zRr&seq=1

Gjørv, O. E. (2011). Durability of Concrete Structures. *Arabian Journal for Science and Engineering*, *36*(2), 151–172. https://doi.org/10.1007/s13369-010-0033-5

Greenspec. (2020). *GreenSpec: Environmental Advantages of Rammed Earth Construction*. Www.greenspec.co.uk. https://www.greenspec.co.uk/building-design/rammed-earth/

Kariyawasam, K. K. G. K. D., & Jayasinghe, C. (2016). Cement Stabilized Rammed Earth as a Sustainable Construction Material. *Construction and Building Materials*, *105*, 519–527. https://doi.org/10.1016/j.conbuildmat.2015.12.189

Keefe, L. (2005). *Earth Building*. Google Books.

https://books.google.com/books?hl=en&lr=&id=cCGAAgAAQBAJ&oi=fnd&pg=PR1&dq=related%3AQPuiWGX3chYJ%3Ascholar.google.com%2F&ots=j-2iTZwkRc&sig=OObC1Ys6Vjg_34FXXJ_5K7N61RA#v=onepage&q&f=false

Kubba, S. (2009). LEED Practices, Certification, and Accreditation Handbook. In *Google Books*. Butterworth-Heinemann. https://books.google.com/books?hl=en&lr=&id=x_Rnb9uIiQQC&oi=fnd&pg=PP1&dq=leed+certification+&ots=LQ5JOJs7HO&sig=F6dIeQGoLzjb6dvxN0mo55ak21o#v=onepage&q=leed%20certification&f=false

Lehne, J., & Preston, F. (2018). *Chatham House Report Making Concrete Change Innovation in Low-carbon Cement and Concrete*. https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

Maniatidis, V., & Walker, P. (2003, May). A Review of Rammed Earth Construction - University of Bath. https://people.bath.ac.uk/abspw/rammedearth/review.pdf

McNeil, K., & Kang, T. H.-K. (2013, March 29). *Recycled Concrete Aggregates: A Review - International Journal of Concrete Structures and Materials*. SpringerLink. https://link.springer.com/article/10.1007/s40069-013-0032-5

Nevill, A. M. (2011). *Properties of Concrete Nevill, 5th Edition - [PDF document]*. vdocuments.mx. https://vdocuments.mx/properties-of-concrete-nevill-5th-edition.html

Pepper, D. (2019). *The Roots of Modern Environmentalism*. Google Books. https://books.google.com/books?hl=en&lr=&id=3ELBDwAAQBAJ&oi=fnd&pg=PT12&dq=environmentalism&ots=_1NUIZCTd3&sig=w0aEtXXZjNyCZdZcFQ6zFq-na4A#v=onepage&q=environmentalism&f=false

Portland Cement Association. (n.d.). *CARBON FOOTPRINT WHAT IS IT? INTEGRATED PAVING SOLUTIONS*. https://www.cement.org/docs/default-source/th-paving-pdfs/sustainability/carbon-foot-print.pdf

Rome, A. *Conservation, Preservation, and Environmental Activism: A Survey of the Historical Literature*. (2003). Retrieved October 27, 2023, from https://archives.iupui.edu/bitstream/handle/2450/664/Conservation.pdf?sequence=1

Scheffer, V. (2013). *The Shaping of Environmentalism in America*. Google Books. https://books.google.com/books?hl=en&lr=&id=kU3-FO_3lKMC&oi=fnd&pg=PP15&dq=environmentalism%2B&ots=WConhSACYg&sig=AT0bEckl0dQS2gZtfY-5llWj-a0#v=onepage&q=environmentalism&f=false

Slanger, D. (2022, June 27). *Low-Carbon Concrete in the Northeastern United States*. RMI. https://rmi.org/low-carbon-concrete-in-the-northeastern-united-states/#:~:text=In%20a%0recent%20interview%20with

United States Environmental Protection Agency. (2023, January 23). *Comprehensive procurement guidelines: Cement and Concrete*. epa.gov. https://www.epa.gov/smm/comprehensive-procurement-guidelines-cement-and-concrete-specifications