Addressing Embodied Carbon in Building Foundations

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Executive Summary

In addressing sustainability within the context of climate change, a great deal of attention has been brought to buildings and construction given the large greenhouse gas emissions associated with this segment of the economy. And while progress has been made towards improving the carbon footprint of buildings, most of that effort has been focused on reducing carbon emissions from building operations. This has been driven in large part through stricter energy codes, energy efficiency initiatives and the addition of renewable energy generation.

Global attention is now turning to the long-ignored issue of the embodied carbon in building materials. This embodied carbon is the carbon emitted in the production, transportation, installation and demolition of materials and it accounts for 11% of emissions globally. With the built environment forecasted to double by 2030, building materials are moving to the forefront as part of the climate solution (UN Environment and International Energy Agency 2017).

This paper will focus on the issue of embodied carbon in building materials by illustrating a specific technological enhancement to concrete foundations which can significantly lower the embodied carbon content of buildings, speed construction, reduce construction risk and lower overall costs. The coupling of this building technology with a prefabricated foundation strategy to reduce carbon emissions and waste associated with Portland cement is particularly interesting within the context of the problem of expansive soils. Expansive soils drive significant carbon emissions in the built environment through the construction and engineering requirements generally specified to mitigate the significant structural damage they can cause. This synergistic approach of combining a modern interpretation of an historical foundation technology with the benefits of prefabrication of building elements will be explored and illustrated with a specific case study of a demonstration building.

In addition to exploring an effective foundation systems solution for reducing the embodied energy in buildings, the paper will also review policy responses emerging to drive this global agenda. Policies being explored range from incentives for alternative materials, to restrictions on the total carbon footprint of materials in new builds. These policies are beginning to appear at the municipal, state and national levels in the U.S., Canada and Europe. Lifecycle analysis, building disclosure labelling and zoning ordinance revisions, are all examples of the exciting initiatives that are currently unfolding. (Embodied Carbon Network, 2018)

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Embodied Energy in Building Materials

While climate change remains a debated topic, it is generally accepted that human activities play an important role in contributing to the greenhouse gas emissions believed to be driving global temperature increases. Scientists warn that without aggressive efforts to limit and reduce carbon emissions, the world could undergo fairly dramatic and possibly dangerous climate changes such as rising sea levels, severe weather events, and food and water shortages. The Paris Agreement reached in 2015, marked a pivotal moment when nations came together to set long-term goals to prevent irreversible climate change. Ambitious targets were set to limit global temperature rises driven by carbon emissions.

No carbon emission reduction strategy would be complete without considering the built environment as it accounts for almost half of total greenhouse gas emissions, more than any other sector of the economy (Fay, 2014.) Most reduction efforts to date have focused on the operating emissions of buildings. This includes enhancements to existing building stocks for improved energy performance, as well as energy performance standards for new construction to avoid developing long-term investments in assets that are energy inefficient. This focus on energy efficiency is illustrated by the current best practice of constructing zero or near-zero net energy buildings. The European Union, in fact, has set an ambitious goal of requiring that all new buildings be nearly net zero energy buildings by the end of 2020. Publicly owned and occupied facilities are required to meet that standard by the end of 2018. (IPEEC, 2018).

While this is important progress toward a built environment that is carbon neutral, the very construction of these high performance buildings implies substantial carbon emissions. In order to achieve low operational energy consumption, a larger proportion of a building's lifecycle carbon emissions can occur with investments in increased insulation, heavier building materials and additional energy efficiency technology. (Thormark, 2001) More material means more embodied energy, defined as the “sum of the energy requirements associated, directly or indirectly, with the delivery of a good or service” (Cleveland & Morris, 2009). Combined with the construction processes involved in building assembly, the embodied carbon of a building’s materials logically becomes even more relevant in low operational energy buildings as this substantial carbon “investment” occurs at the beginning of the building lifecycle.

Global building operations and construction together account for 36% of energy use and 39% of energy-related carbon dioxide (CO2) emissions. Just the material use in buildings alone is estimated to account for 28% of these emissions, or 11% of total carbon emissions related to global human activity (UN Global Status report 2017 page 8). With approximately 6 billion square feet of new building construction every year in the United States, for example, it is estimated that the embodied carbon emissions from the construction processes and materials alone has a carbon footprint of 150 million metric tons. That embodied energy content considers the lifecycle of the materials from mining, manufacturing, and construction. With 25 million metric tons of carbon emissions every year estimated from the operation of that new space, we can extrapolate that the embodied carbon content of materials represents about six years of building operations. This is before building operations emissions even begin and is well into some of the shorter time-frame carbon reduction goals that have been set in place in more aggressive policy regimes like the European Union. (The Total Carbon Study, 2015). Working toward a future that contemplates zero-emission, fully decarbonized buildings means the opportunity to find more sustainable practices in the building materials and construction sector is large and meaningful.

Building Foundation Systems

Foundation systems are a natural place to look when seeking out opportunities to reduce embodied carbon in buildings given the ubiquitous use of high embodied content materials and the sheer volume of material required to properly support structures. Foundations are largely comprised of steel reenforced concrete given its superior performance characteristics and the flexibility of the materials. Portland cement and steel represent most of the emissions attributed to building materials in general because they require energy intensive manufacturing processes, they are widely used, and because of the sheer volume of material made and placed in building construction. Portland cement, effectively the glue for aggregate in modern concrete, is the major climate offender, accounting for approximately 5 percent of global carbon emissions alone. (Rubinstein, 2012). Concrete is the most widely used building material in the world after gravel

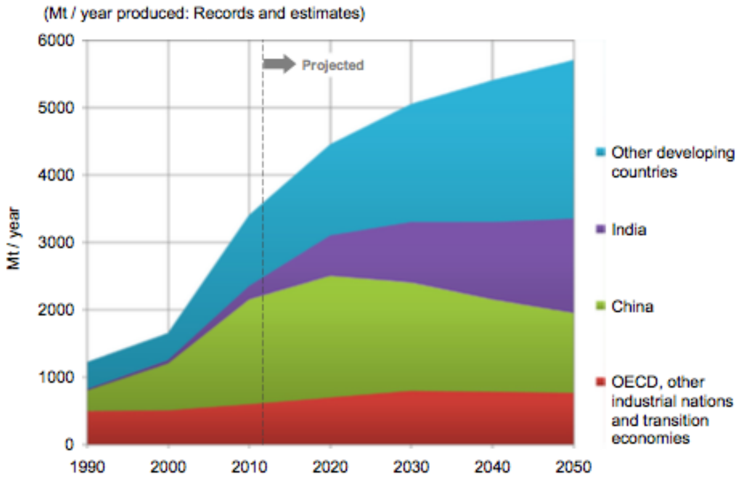

Figure 2. World Portland cement production 1990–2050.

Figure 2: World Portland cement production 1990 - 2050
Source: Imbabi, et al. 2012

and sand with some 2 billion tons used per year. And the amount of concrete used is forecasted to rise drastically by 2050 with the use of the material growing especially fast in emerging economies. (Crow, J) (Source: New Carbon architecture pg 69)

This makes concrete a prime candidate for which to explore more sustainable construction practices, including opportunities to reduce or eliminate the amount of the material needed for foundations. The concrete mixes used in building foundation systems typically have a Portland cement content ranging from 7% - 15% content by weight depending on the mix design needed for structural strength. (NRMC 2008). A standard unit of measurement for delivery and installation of concrete is a cubic yard which weighs approximately 3,800 pounds. That means, on average, a cubic yard of concrete has in excess of 400 pounds of embodied carbon. (Marceau, et al. 2007). Any opportunity to reduce the Portland cement content of a foundation system pays significant climate dividends.

Expansive Clay Soils

Any discussion about foundation systems has to begin with the impact of site soil conditions on foundation design. This is especially true when expansive soils are present. Expansive soils present geotechnical and structural engineering challenges worldwide. The remediation and repair costs associated with the damage caused to buildings by expansive soils run in to the billions of dollars each year (Jones, et al. 2012). It’s estimated that each year 150,000 new homes built in the United States experience at least minor damage from the shrinking and swelling that occurs with expansive clay soils. Over 10 percent experience significant damage. And the American Society of Civil Engineers estimates that 1/4 of all homes in the United States have some level of damage caused by expansive soils. The financial impact of expansive soils causes greater financial loss to property owners than earthquakes, floods, hurricanes and tornadoes combined, much of it uninsured (Holtz, et al. 1978). And, while it is beyond the scope of this paper, one can only imagine the carbon footprint related to the deconstruction, repair and reconstruction of buildings related to soil heave.

Foundation failures in commercial and residential projects due to expansive clay soils have led engineers and contractors to design solutions requiring more concrete and more steel to manage these difficult soils. This is not an exact science and by definition substantially increases the embodied carbon of the build. Another impactful practice that is both costly and adds significantly to the embodied carbon in new construction is the geotechnical practice of removing and replacing building site soils in an attempt to mitigate the shrink swell cycle of expansive soils. This entails excavating existing site soil, hauling it off and replacing it with non-expansive fill brought to the site to a depth that's determined to be necessary to prevent excessive soil heave. The primary disadvantage of this practice is, first and foremost, the sheer cost of it as will be illustrated in our case study. This renders many projects financially unfeasible and can lead to shortcuts taken in the interest of cost reduction with the subsequent future consequences in building performance. Second, the carbon emissions associated with the remove and replace practice can be substantial.

Climate change enters the equation as well as expansive soils shrink and swell based on moisture content. Changing weather patterns over the coming decades are expected to result in increasing temperature, drier conditions and increased frequency of extreme weather events (CSIRO, 2007). By definition this will be disruptive to soil performance under existing buildings, and calls for new engineering considerations on new buildings. The revival of an historic foundation technology with a modern application coupled with new trends in building component fabrication offers an exciting opportunity to both improve the structural performance of buildings while lowering material content and, by extension, lowering the embodied carbon.

Screw Piles

In the search for effective, resilient foundation technologies with lower embodied carbon, it can be instructive to look back to historical building methods for opportunities to leverage solutions that have been forgotten. Their viability can be renewed within a modern context and with modern engineering. One such historical foundation technology is screw piles. Screw piles are a nineteenth-century foundation engineering solution that was used successfully throughout the world to support large scale civil engineering projects, like lighthouses, bridges and ocean piers. The first known installation of a screw pile foundation for a building was the 1838 vintage Maplin Sands Lighthouse. And between 1861 and 1880, at least sixty lighthouses were

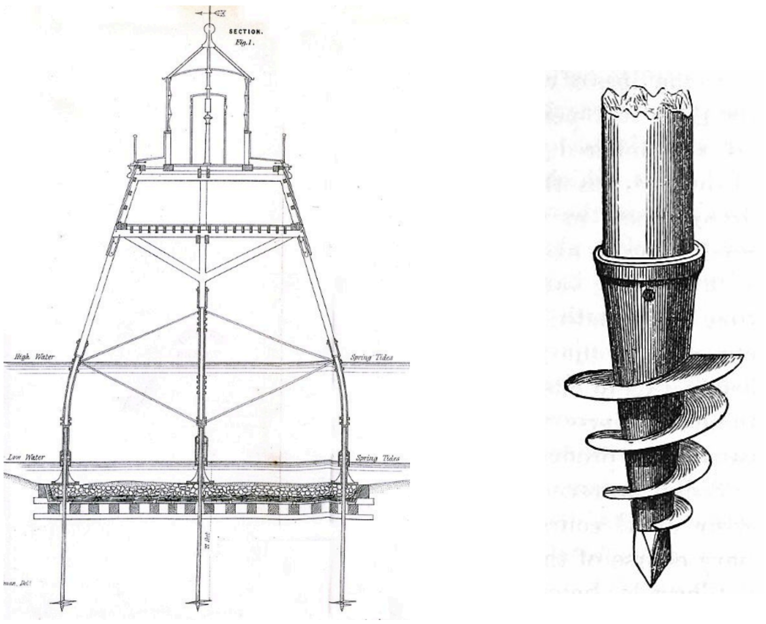

Figure 3: Screw pile

constructed in the US using a screw pile foundation system, many of which still stand. (Lutenegger, 2011).

While this foundation system faded in popularity as other engineering solutions were developed, they have found new interest due to the advantages of easy and fast installation, bearing capacity immediately after installation, flexibility on length to suit site specific conditions and economic competitiveness. The revival of screw pile foundation systems can be found in the evolution of the modern day threaded steel micropile, or ground screw. Ground screws were first developed in Germany in the 1990s, and provide a modern foundation solution that can eliminate or greatly reduce the concrete needed for a foundation. This modern version of the screw pile consists of a steel tube with a welded, continuous spiral of steel threads on the lower section of the pile and has a tapered tip. Grounds screws are also galvanized to resist corrosion. They are installed into the building site by applying torque and downward pressure. No grouting or concrete is involved, ground disturbance is minimized and the ground screw can be immediately loaded after installation. It resembles, and indeed functions, much along the lines of the physics of a wood screw. This includes the ability to uninstall the ground screw if it is improperly placed or after a building is demolished.

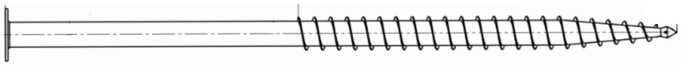

Figure 4: Steel threaded micropile or ground screw

Aside from the disintermediation of a high embodied energy material like concrete, the ground screw enjoys important installation and performance advantages relative to a conventional poured in place concrete pier. This is best illustrated in **figure 5.** One not so obvious advantage is the ability to adjust the shaft length of a ground screw to accommodate site soil conditions, particularly in expansive clay soils. The active moisture zone in expansive soils is typically considered to be from grade to approximately five to seven feet below grade. It is in this zone where moisture content of the soil can vary significantly depending on climate conditions. In extended periods of drought, expansive soils will tend to shrink, disrupting the bearing surface and adhesion of foundation piers. With excessive moisture due to precipitation, broken pipes or other sources, the soils in this active zone can swell, exerting enormous forces on buildings. With the flexibility to extend ground screws to an optimal soil bearing layer below this active moisture zone, the engineer can help isolate the building from the shrink swell cycle of

Figure 5: Concrete versus Ground Screw

expansive soils. With improved foundation performance, future potential damage can also be mitigated along with the associated embodied carbon footprint of repairs. The ground screw alternative to concrete foundation piers can also speed installation, eliminate material waste, improve installation precision and consistency of materials, lessen impact on the building site, eliminate excavation and removal of site soils, and allow for site restoration to natural conditions with minimal effort. With the above performance advantages for pier and beam foundation systems, the door is open to consider applications for widely used slab on grade approaches and prefabrication innovations.

Prefabrication: Disrupting the Construction Waste Stream

The material waste associated with building construction has a significant environmental impact and is often an ignored factor, especially relative to the time and cost associated with the build itself (Shen et al, 2002). In the United States, it's estimated that 29% of the solid waste stream is in fact associated with construction waste (Rogoff et al, 1994). With rapidly growing urban populations and the sheer scale of new construction contemplated to accommodate global needs over the next 30 years, the need to reduce the escalating volume of solid waste destined for landfills is urgent as landfill capacities are challenged. One answer to the waste stream equation is the prefabrication of building components.

Prefabricating building components in general has many advantages including better quality control, reduced costs, elimination of weather delays and less waste. Lowering waste also translates into less building material and a lowered embodied carbon content of the building component. Prefabrication strategies applied to building foundations specifically target high embodied energy Portland cement and eliminates a great deal of construction risk. This can significantly reduce the amount of concrete needed along with the associated waste.

Typical waste for in situ concrete installations is approximately 20%. Prefabrication of concrete building elements has been demonstrated to reduce this waste by up to 90%. A 90% waste reduction implies an 18% savings in total material (Vivian, et al. 2007). The significance of that waste reduction, just in terms of material costs and embodied carbon, is significant as illustrated in the example of a 1,250 square foot new home concrete foundation slab build in South Central Texas. A 1,250 square foot home will typically require 16 yards of concrete for the surface 4 inch slab, with an additional 16 yards for the turn down beams depending on slab design. With an 18% differential waste factor applied between prefabrication versus on site build, this implies almost 6 yards of concrete allocated to waste. At a current price of approximately $98 per yard, the concrete material costs of the slab is $3,136. Reducing waste by 18% net yields a potential cost savings of $565.

The impact on the embodied carbon of the foundation system is even more interesting. At approximately 400 pounds of embodied carbon per cubic yard of concrete, prefabrication with the associated waste reduction could reduce the carbon footprint of the building by about 2,400 pounds of carbon. Saving 2,400 pounds of embodied carbon by reducing concrete waste through prefabrication strategies can then help to offset the embodied carbon found in the reenforcing steel (rebar) used in the four inch slab portion of the foundation. Rebar used on foundation systems in the United States are comprised of 97% recycled steel. (https://www.concreteconstruction.net/how-to/materials/from-old-cars-comes-rebar_o) Recycled general steel has an embodied carbon content of .42 pounds per 1 pound of steel. (Burners-Lee, 2011.)

Number 4 Rebar weighs .668 pounds per linear foot. For a 25 foot by 50 foot slab (or 1,250 square feet), 1,754 linear feet of number 4 rebar would be specified at an 12 inch grid spacing for the four inch slab yielding a total rebar weight of 1,733 pounds. (https://www.vcalc.com/wiki/KurtHeckman/Rebar+Calculator) Thus the total embodied carbon in the reenforcing steel for the four inch slab section would be 728 pounds of carbon. The 2,400 pounds of carbon waste reduction value of the concrete then translates into fully offsetting the carbon content of the steel.

The carbon reduction power of prefabricated foundation elements gets even more exciting when coupled with ground screws. By providing a better bearing surface below the risk zone of expansive soils, the turn down beams of the slab foundation can be eliminated. This reduces total concrete need by an additional 50%. In our example, this would translate to 16 yards of concrete, or an embodied carbon reduction of 6,400 pounds. The associated steel reenforcement would also be eliminated yielding an additional 728 pounds of carbon. These embodied carbon savings can then be applied to the carbon budget recycled steel ground screws which will vary based on final slab design. This innovative strategy is but one example of successful efforts to improve building performance, improve construction processes, lower embodied carbon and is illustrated in our case study of the Eco Centro demonstration building.

Case Study: Eco Centro

The Eco Centro case study illustrates an effective systems approach to foundation design that reduces the embodied carbon footprint of the building, improves building resilience in the face of difficult site conditions, improves the construction process and greatly reduces costs. This demonstration structure will be constructed at the Eco Centro community outreach center for environmental sustainability in San Antonio, Texas.

The building is designed as a small demonstration project illustrating the benefits of compressed earth block (CEB) wall construction. CEB is considered heavy masonry with a low embodied energy content. The building footprint is 15 feet by 12 feet and will be constructed of approximately 2,232 CEBs stabilized with 5% Portland cement. Portland cement has a carbon footprint of 2 pounds of carbon per 2.2 pounds of cement. (Burners-Lee 20***) With each CEB weighing 22 pounds, that translates to 1.1 pounds of Portland cement per block, or approximately 2,234 pounds of embodied carbon for 372 square feet of building walls.

The build site itself sits on highly expansive soils. As previously discussed, this soil type presents a high risk for future structural damage. The geotechnical engineering report stipulates a building area to include three feet beyond the building perimeter dimensions, or 18 feet by 15 feet. It further stipulated a common remediation strategy of removing the soils under the building area to a depth of 10 feet and removal from the building area. After further site prep, the design calls for placing four feet of the removed soil in the building area and compacting it to within six feet of existing grade. Next, six feet of select fill is to be delivered to the site, placed and compacted to restore to grade and complete the building pad. Laboratory testing is required per code for each two feet of compacted lift (Drash. 2007)

This can be an extraordinarily expensive endeavor as illustrated with local contractor pricing in Table 1. While ten feet of remove and replace is an extreme example, it is not uncommon to see recommendations for four to six feet of remove and replace to mitigate the effects of expansive soils on buildings in many parts of the U.S., particularly in Texas. This recommendation renders the Eco Centro project uneconomic or worse, budget constraints would dictate a compromise solution with cost implications in the future. Remove and replace also amplifies the embodied carbon in the build with the fuel consumption related to transportation, site excavation, grading and compaction.

Table 1	Cost Per Cubic Foot	Total
Excavation	$15.41	$2,774.00
Recompact 4’ Site Soil	$10.80	$1,944.00
Remove/Haul Off	$10.67	$1,920.00
Select Fill Delivery	$9.33	$1,680.00
Compact Fill	$12.58	$2,264.00
Laboratory Testing	$6.67	$1,200.00
Total	$65.46	$11,782.00

Table 1: Cost estimates provided by Modern Earth Construction based on local rates.

In contrast, the systems approach illustrated in Figure 6 incorporating ground screws and prefabricated foundation elements has a profound effect on the foundation cost, the speed of construction and the embodied carbon content of the building. The production advantages inherent in this system approach, as demonstrated earlier, can reduce concrete and steel materials by over 50%, reduce onsite labor and reduce the construction time frame. Ground screws also eliminate the need for removing and replacing the expansive clay soils, an enormous cost savings. Properly specified shaft lengths for the ground screws allows for precision placement of the supporting piers below the active moisture penetration zone isolating the prefabricated concrete foundation beams from soil heave. Further design enhancements elevate the four inch foundation slab resting on the beams creating a void that further relieves any potential soil heave impact on the building. All of these advantages add up to a more affordable and more resilient building with more precise engineering performance.

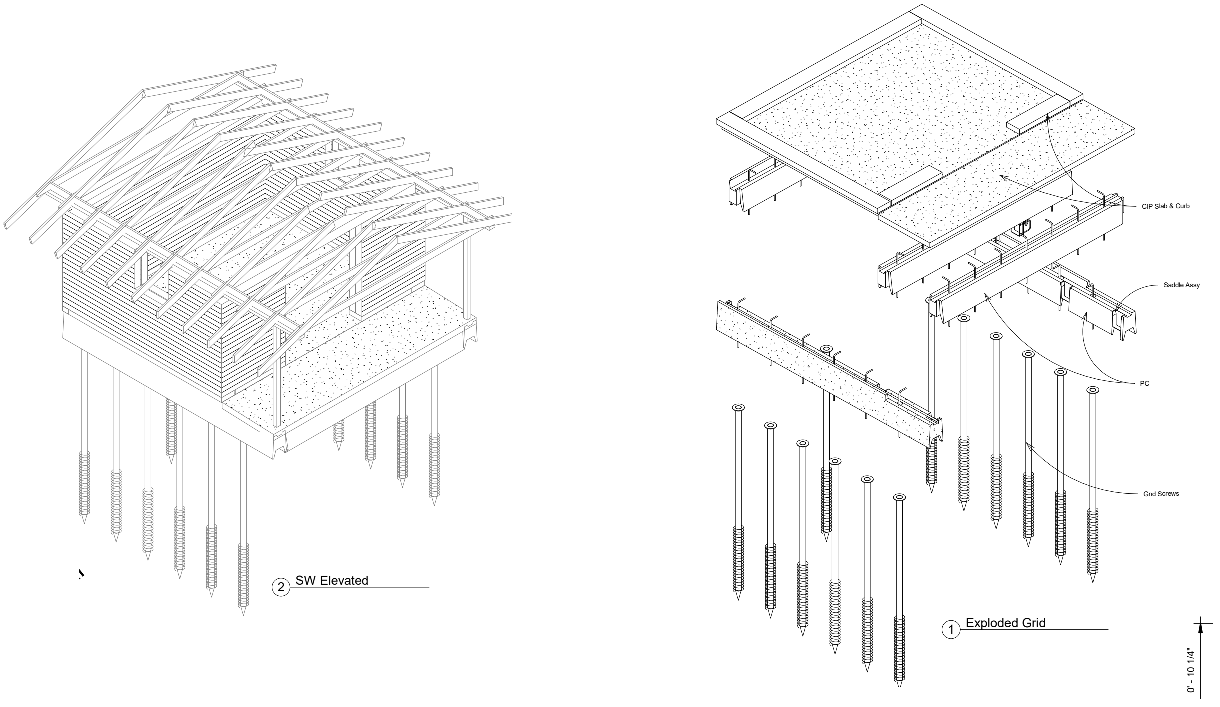

Figure 6: Courtesy of Ankor Foundations and Maritech Engineering

The Eco Centro case study illustrates how innovation and engineering can help not only reduce the embodied carbon in buildings and their foundation systems, but can also lower costs and improve building performance and resilience.

Policy Initiatives

Demonstration projects like Eco Centro provide a roadmap and examples of how building design and material choices can evolve to help meet global sustainability goals. However, the construction industry is massive and can be slow to adopt new technologies given the engineering risks. This is compounded with the loss of skills related to historic building technologies that often have a lower environmental impact. How then can policy initiatives help to encourage the adoption of these types of innovations and improvements to the built environment? While the adoption of building energy codes seems to be growing over the last decade, those who still do not have energy codes represent two-thirds of the countries in the world. (Global Status 2018) Despite that, there are interesting policy initiatives emerging in international and domestic markets.

In France, incentives are being offered for meeting embodied carbon as well as net-zero energy targets. While this is voluntary today, it will be mandatory in 202. In the Netherlands, new buildings have to submit estimates of embodied greenhouse gas emissions to receive a permit. In Vancouver, British Columbia all rezoned buildings must report embodied emissions. These calculations include all structural and envelope elements of the building. (Embodied Carbon Network (2018).

In the United States, state and local government is where the opportunity lies as building regulations, codes and permits reside at this level, and there interesting concepts are beginning to emerge. Local building codes and regulations have generally been focused on life, health and safety issues. But more recently, they have begun to incorporate greater energy efficiency standards to address operating emissions from buildings. As of yet, however, codes are not incorporating rules to limit the carbon foot print of materials used in building construction. We're beginning to see the first ideas beginning to emerge about how to affect that change.

Two counties in California recently issued a grant to a local consortium to help develop building code amendments that will create limits to the embodied carbon in concrete used in new buildings. (Ecological Building Network, 20??) Other jurisdictions are beginning to look at local government purchasing decisions and assessing the embodied carbon contribution of building materials. In the State of Washington, the American Planning Association Chapter outlined a number of strategies to reduce emissions in the construction materials supply chain including rewards for reducing the cement content of concrete, requiring Carbon Control Plans from contractors, incentives for green building projects and requiring recycled material use to the maximum possible. (APA Washington Chapter, 20??). The state of Minnesota

Finding a way to monetize the carbon content of building materials seems to be emerging as the mechanism of choice for behavioral change in construction. The two leading strategies proposed have been either a carbon tax, or carbon trading markets also known as emission trading schemes. While carbon trading markets continue to emerge, the markets have been slow to develop and price volatility has been severe (Zhang, et al. 2018). In spite of that, it is notable that the world's two largest greenhouse gas emitters, China and the United States, have existing carbon markets with carbon pricing instruments. (World Bank, 2014). How specifically large emitters will be "punished" through taxes and low emitters will be rewarded with certified credits to enable trading markets to exist seems to be a relatively open question. Until that happens, it is uncertain exactly how these markets will effect material design, production and consumption.

In the end, the consensus seems to be that a carbon tax is the most practical, efficient and effective mechanism for spurring a transition to more climate-friendly building materials. In fact, some of the largest fossil fuel companies themselves have recently advocated a tax on carbon emissions. (NY Times, 2015). Industry views a carbon tax as a much easier program to administer and provides an efficient and predictable policy against which long term capital commitments can be made. How these tax revenues will be spent is as yet unclear, although some ideas considered call for reductions in other taxes, investments in renewable energy and public transportation.

As an example, British Columbia successfully enacted a carbon tax in 2008 and has inspired a nation-wide Canadian carbon price. While the carbon tax only applies to the purchase and use of fossil fuels, British Columbia claims that it demonstrates that it is possible to reduce emissions and grow the economy based on excellent GDP growth subsequent to enactment of the tax. The program also calls for increasing the carbon tax rate from its present level of $35 per ton of carbon emissions to $50 per ton by 2021. The provincial government intends to use these new revenues to encourage new green initiatives and to provide tax and other affordability relief to residents of the Province. (British Columbia's Carbon Tax??)

And finally, there are nonprofit initiatives providing leadership to both governmental agencies and private entities to help decarbonize the built environment. An excellent example of this is the Architecture 2030 organization which has developed that Zero Code and Carbon Smart materials palettes. These tools provide practical and immediately applicable strategies to help address the issue of embodied carbon in the built environment. (Architecture 2030)

Conclusion

The accounting concept of the triple bottom line, people, planet, profit is one of the key touchstones in sustainable development. The built environment offers tremendous opportunities to address all three in constructing healthy, net-zero energy and low embodied carbon material structures. This is particularly important given the large contribution of the building sector of the economy to climate change. The embedded carbon content of foundation systems in particular entails a building element that uses large amounts of those building materials that carry some of the highest carbon footprints. Finding ways to reduce the need for those materials and for improved construction processes while simultaneously improving building performance seems a daunting but worthy goal. The Eco Centro foundation design provides a roadmap to one solution that is robust and all less expensive than conventional foundation approaches. Leveraging a synergistic strategy that blends advanced prefabrication strategies with refined historic building technologies demonstrates what is possible. Improving foundation system performance in expansive soil conditions takes it one step further into climate resilience by creating a foundation system that is isolated from shifting hydrologic patterns.

How governing bodies incentivize or punish within the context of embodied carbon in building materials remains to be seen. Already forward thinking jurisdictions are proposing and phasing in policies targeting the large contribution of the built environment to climate change. By demonstrating what is possible through private innovation, we can add to the triple bottom line with the entrepreneur’s credo: faster, better, cheaper.

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