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Embracing Carbon Abatement in Concrete for the Construction of Electrical Utility Networks

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SUMMARY

Cement production is a major contributor to the global CO₂ emissions that are partially responsible for climate change and its effects. Therefore, any new placement of concrete has a potentially unseen carbon footprint. There are several existing and emerging techniques for carbon abatement in the cement industry; however, many of these methods make alterations to the well-known behaviour of ordinary Portland cement concrete. The necessity to decarbonize requires engineers and owners to familiarize themselves with carbon abatement in concrete materials. Electric utilities are in a good position to take a climate leadership role by adopting low carbon materials while strategically accepting potential risks that come with doing so.

KEYWORDS

Sustainability, Concrete, Decarbonization, Climate Leadership

INTRODUCTION

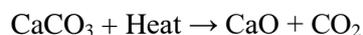
It is no longer a secret. It should no longer be a taboo. We, the population of this planet, have a problem. The solution is to rapidly decarbonize our society to limit the damage of climate change. The need for decarbonization is increasingly becoming better understood in the power generation and delivery sector. Many large and small utilities in the United States are pledging drastic reductions in their carbon output in the next few decades, all while attempting to increase reliability by constructing resilient transmission networks in the face of physical and cyber threats. But carbon emissions do not only result from power generation. Construction is also a major contributor to greenhouse gas emissions, prompting the question: how can utilities, and the engineering firms that support them, play a leadership role in decarbonizing construction in tandem with their efforts to decarbonize power generation?

Much of the emissions involved in the construction and renovation of substations and transmission networks occur before the materials arrive at the site. (Note that, in this paper, we use the term “transmission networks” to mean the physical infrastructure involved in the delivery of power, including transmission and distribution lines, switching stations and substations.) The US Environmental Protection Agency (EPA) estimated that 29.7% of all US greenhouse gas emissions come from heavy industry [1]. Cement production and iron and steel production account for almost half of those industry emissions. We recognize that transmission networks represent a small portion of the overall construction industry; however, utilities are demonstrating their interest in decarbonization and the type of relatively small-scale engineering and construction applications common to grid construction may be advantageous in the adoption of new technologies.

In this paper, we review the processes by which one of the main material components of utility network construction, concrete, contributes to greenhouse gas emissions. We review the current and potential means by which the concrete and cement industries can reduce or eliminate their carbon emissions. We have chosen to divide carbon-reducing methods into two distinct categories: those which do not affect current structural specifications and design procedures for these materials, and those which may alter the design process by fundamentally altering the respective construction material. This paper concludes with a discussion of the role that utilities can play in advancing decarbonization in the construction industry, as well as the potential advantages and disadvantages of integrating decarbonized materials into the construction of substations and power delivery networks.

CEMENT MATERIALS

Concrete, commonly used in substation and transmission networks for shallow foundation, pile cap and drilled pier construction, is primarily composed of water, aggregate, and cement. The latter component is primarily composed of Calcium Oxide (CaO), otherwise known as lime. The lime in common cement is the product of a process called clinkering, wherein Calcium Carbonate (CaCO₃), commonly called limestone, is subjected to temperatures on the order of 1600°C. The representative reaction is given by:



The production of lime therefore emits greenhouse gasses in two processes, distinguished herein because they may require distinct approaches for decarbonization. The energy emissions are those resulting from the burning of fossil fuels to heat the cement kiln to the required temperatures. The process emissions are the result of the chemical reaction, i.e. the release of carbon dioxide with the formation of Lime.

Reduce, Reuse, and Recycle

The “3 R’s”, reduce, reuse, and recycle, is a common term for discussing the sustainability aspects of any project. Reducing the amount of concrete (and therefore the amount of cement) used on a project can be achieved through competent engineering work that results in designs that are not overly conservative. Modular construction with precast concrete elements results in material reduction due to tighter tolerances that are only achievable in precasting facilities. Precast concrete components are not

new in substation constructions and have been increasingly utilized. In addition, the proper use of supplementary cementitious materials can directly reduce the quantity of cement in a specific concrete mix [2]. Enhanced understanding of kiln performance allows for greater energy efficiency at the cement production site. For example, Mahmoud et al. [3], Mittal and Rakshit [4] and Terblanche [5] report a potential energy savings at several cement plants by examining the heating profile of the kiln and implementing a system that better recycles waste heat energy, saving carbon emissions and energy costs.

Reuse of existing structures and foundations is common when feasible, given the preference for upgrading aging substations over constructing new facilities. Hardened concrete can be recycled as a coarse aggregate in new concrete. However, concrete made from recycled concrete aggregate can be susceptible to deleterious deterioration resulting from contamination in the sourced construction debris. Such contamination can therefore limit the usefulness of concrete recycling, or, worse, create unsafe conditions in the resulting construction [6].

Ultimately, the traditional “3 R’s” provide readily available solutions to reducing the carbon footprint of the cement industry. They are already commonly used across the construction industry because they are all advantageous for reducing cost and, as with modular construction, improving schedule performance. Considering the current state of greenhouse gas emissions as weighed against the cost incentive and efficacy of the 3 R’s, complete decarbonization appears to require a fourth R: Reinvent.

Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) is the broad terminology for technologies that remove CO₂ directly at the emission source and the subsequent processes by which the carbon, either in solid or gas form, is stored or sequestered underground or otherwise utilized. CCS is a unique solution because it is a potential solution that simultaneously decarbonizes both cement energy and process emissions, while preserving the specifications and design practices for structural concrete. Despite some challenges with CCS implementation [7-9], CCS systems have been successfully employed at thermoelectric power plants. There are several hurdles to installing CCS systems that have limited its deployment to cement production facilities and its overall efficacy for decarbonization. The most notable hurdle is that the CCS process requires energy and water. If the upstream methods for providing those key ingredients are not decarbonized and sustainable, the downstream effect can be a net increase in CO₂ emissions or water pollution. Additionally, storage of CO₂ can pose a challenge. Simply storing CO₂ in one form or another would be an added cost to the cement producer, and the potential leakage of the byproduct into groundwater is a serious risk [10]. Ultimately, the lack of adoption of CCS in the cement industry is a result of the almost complete lack of economic incentive for doing so. Without a government-enforced carbon tax, or any economically viable use for the byproducts of CCS, there have been few, if any, good reasons to install it other than its benefits for decarbonization [11]. However, there are several relatively new, though still small-scale technologies that are attempting to create economically viable markets for the byproducts of CCS.

An increasing number of ready-mix producers are employing relatively new technologies that utilize CO₂ in the batching process by adding it into a fresh concrete mix. One carbon utilization method was developed by CarbonCure Technologies in Dartmouth, Nova Scotia. The technology has recently received attention as the one of the 2021 winners of the NRG COSIA Carbon XPRIZE. Not only do such technologies provide a viable method for carbon storage as mineralized limestone within a finished concrete structure, but CarbonCure claims an increase in strength of up to 10%. Concrete strength increase validates a reduction in the cement content of mixes that are batched with this method. Therefore, this method can be categorized as one for reducing the carbon footprint by reducing the amount of cement in the mix, as well as a carbon storage, as CO₂ must be captured from other industrial processes. CarbonCure reports a 25 lbs CO₂ saving per yard of ready-mix concrete when compared to traditional methods, and as high as 40 lbs CO₂ savings in precast applications [12]. A total amount of concrete utilized in a substation project varies significantly depending on factors such as project size, voltage level, or foundation types. In one example of a recently completed 138kV substation project with the approximate project size of 90,000 sq.ft. in the Northeastern US using drilled pier foundations

with a range of diameters and lengths, the estimated total amount of concrete was 676 cu. yds. The use of CarbonCure concrete on this project would have prevented the emission of approximately 8.5 tons of CO₂ into our atmosphere. For context, but not for discouragement, global emissions are typically measured in gigatons.

Carbon utilization is also being put into practice by Solidia Technologies in Piscataway, New Jersey. Solidia uses a combination of its trademark non-hydraulic cement and a CO₂ injection to the batching process that reacts with the cement to form calcium carbonate. Solidia reports a 30% reduction in CO₂ energy emissions compared with those of ordinary Portland cement, as well as up to a 100% reduction in water use. The result is a reported reduction of 550kg of CO₂ per ton of cement [13]. Assuming a 94-lb bag of Portland cement yields 4.5 cu ft. of concrete, our example substation project could have saved and stored 115.5 tons of CO₂.

As viable markets for captured carbon require both safe storage and the creation of demand for the product, the storage of captured carbon in the form of artificial aggregates is another relatively new idea for increasing the economic viability of CCS. One method being pioneered by the company Blue Planet in Los Gatos, California is the conversion of captured CO₂ to carbonate, which can then be used to create a synthetic limestone. By coating a rock nucleus with a variable number of layers, artificial aggregates of varying sizes can be manufactured. The company reports that each ton of artificial aggregate sequesters 440 kg of CO₂ [14]. Assuming normal weight 145pcf concrete that is composed of 75% aggregate by weight, our example substation project could have stored 481.5 tons of CO₂.

Decarbonizing Cement Production Energy Emissions

Methods for decarbonizing energy emissions involve replacing fossil fuels with zero or net-zero alternatives for heating the cement kiln. Directly electrified kilns can be used in place of fossil fuels; however, the relative cost of renewable electricity versus that of fossil fuel upstream sources still favors fossil fuels. The dilemma is therefore similar to that of CCS, i.e. without external economic influence, cement producers do not have economic motivation to electrify [15-17]. Another commonly proposed substitution for fossil fuel combustion is hydrogen combustion. Hydrogen-fueled cement plants have been, and are being constructed, primarily in Europe where regulated carbon pricing makes doing so economically viable [18][16]. The use of biomass in place of fossil fuel is another potential solution in the cement industry that relies on the carbon-neutral cyclical nature of biomass, i.e. the amount of CO₂ released by the combustion of biomass is the same amount that a plant would remove from the atmosphere during its growth, or release into the atmosphere during its decay [19][20]. The main advantage of these methods is that they do not alter cement chemistry, and thereby do not alter the specifications or design process for the final product, concrete.

DISCUSSION

What role can utilities play in decarbonizing construction?

American utilities are already engaged in large-scale decarbonization efforts in the energy sector, emphatically committing to the fight against climate change. For example, in 2019, Duke Energy announced its 2050 goal for net zero emissions [21]. In 2018, Pacific Gas & Electric (PG&E) announced it would cut roughly 10% of its 2018 emissions by 2022, on its way to a company goal of 55% renewables by 2031 [22]. Exelon remains “the nation’s largest producer of carbon-free electricity” and has pledged to reduce its emissions to 50% of 2015 levels by 2030 [23]. National Grid is targeting net-zero emissions by 2050 [24]. Public Service Enterprise Group (PSEG) has recently accelerated the target date for accomplishing its net-zero goals to 2030 [25]. Decarbonizing the construction of their new and upgraded infrastructure is a natural complement to their already active decarbonization efforts.

In addition to efforts to cut carbon emissions, U.S. utilities are also demonstrating a commitment to supplier diversity and racial equity [26-34]. Air pollution and climate change are both disproportionately affecting poor and minority communities [35][36]. Therefore, decarbonizing construction in tandem

with energy production is a complimentary goal to the ongoing efforts towards racial equity. In fact, one possible solution could be analogous to many supplier diversity efforts. Utilities may build preferential relationships with construction contractors based on the carbon footprint of their material suppliers. Such an effort would provide the economic incentive for something like the implementation of CCS at cement and steel production facilities.

What role can engineers and contractors play in decarbonizing construction?

In a recent interview on the podcast “The Interchange,” Rebecca Dell, Industry Program Director at the Climate Works Foundation summarized a dilemma facing engineers and construction contractors [37]:

If you have a great idea for a new cement chemistry and you bring that to a contractor or a structural engineer, there’s a good chance that the response you’re going to get is “Oh, that’s super interesting! Why don’t you build YOUR bridge out of it and come back in forty years and we’ll take a look at how the bridge looks and then we’ll talk.”

In other words, the risk associated with uncertainty in the performance of novel construction materials is more so assumed by engineers and contractors, and less so by the material producers. As engineers, contractors, and owners, we must recognize that we do not have 40 years to wait and “take a look” and then talk. We have an obligation to ourselves and to future generations to familiarize ourselves with novel products that might be beneficial to fighting climate change so that we can better understand the risks and begin to specify low carbon alternatives now.

Should transmission networks be considered good candidates for decarbonized materials?

In addition to what should be the obvious benefits of decarbonization and the good public relations that come with reducing carbon emissions, some features of networked design may be beneficial for the implementation of new concrete technologies. Substation yards and transmission networks are often composed of multiple separate foundations for equipment and designed with redundancies that allow the station to perform its functions when parts of the station are intentionally or accidentally taken out of service. Identical independent foundations are often constructed at multiple different locations. Constructing a limited number of foundations using low carbon concrete constituents would provide an opportunity for controlled long-term experimentation in real construction exposed to the elements. If any of these relatively new concrete technologies were to experience long-term unforeseen deterioration, the redundant nature of substation design could allow for the replacement of that portion of the station with a more reliable alternative. While such a replacement would be relatively inconvenient from the viewpoint of the utility that operates the substation, it would also be viewed as very convenient when compared to larger, monolithic construction of large industrial or residential facilities.

There are, of course, barriers that utilities must consider in implementing decarbonized materials. Novel additions to concrete mixing may also lead to novel and unexpected deterioration mechanisms, as was the case with Type III cements and Delayed Ettringite Formation, or ordinary Portland cement and Alkali Silica Reaction (in the presence of siliceous aggregates). Substations and transmission networks are critical infrastructure. Modern society depends on electricity for all the necessities and many of the luxuries of daily life, and the necessity of electricity is even greater under the threat of hazardous events that strain infrastructure to its designed capacity limits. For design purposes, substations and transmission networks are commonly designed to criteria for Risk Category IV structures, representing the structures that, if they were to fail, would create the greatest level of harm to the surrounding communities. The risk designation of these facilities is a barrier to using new construction as a test case for materials with unknown reliability, especially given that the reliability of concrete that is batched with ordinary Portland cement derives from centuries of use, and the ensuing lessons learned from its use.

CONCLUSION

On the topic of decarbonizing construction of transmission networks, the review presented in this paper makes it clear that there are existing options and emerging technologies with the real potential for moving the carbon output needle to zero. However, many of the technologies remain unproven at the scale necessary to achieve net zero or net negative carbon emissions for the concrete industry. In addition, transmission network owners and operators may be hesitant to treat their facilities as the test cases for these nevertheless necessary changes to our means of construction. In other words, we must decarbonize, which means we must tweak the concrete formula, which then means we must be left with less certainty in the long-term performance of the material we know so well. As consulting engineers, we don't believe it to be implausible that low carbon concrete can be adapted into our designs and specifications, and we are preparing ourselves to support the effort. As electrical utility owners, we hope that utilities are ready to take this step with us and accept that we all may need to accept additional risk in the process. After all, as humans, we cannot afford to wait.

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