Carbon Sequestering Bio Concrete as a Solution to Growing Atmospheric Concentrations of CO_2

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High levels of anthropogenic carbon dioxide (CO_2) emissions into the atmosphere are propelling climate change, which has been proven to be highly detrimental to the planet. Cement production for the construction industry is a leading cause of these harmful carbon emissions. This project introduces a potential solution to this issue in the form of a new biological concrete that is treated with carbon sequestering bacteria of the *Bacillus* family to remove CO_2 from the atmosphere. The consolidated research presented in this project will explain the biology behind this process, and how it can be implemented in construction to reduce atmospheric CO_2 concentrations. Additionally, this paper will evaluate the feasibility of implementing CO_2 sequestering concrete in construction on the basis of its strength and cost. Finally, new knowledge will be recorded in the form of interviews of industry professionals to clearly illustrate how carbon sequestering bio concrete could be implemented in construction.

Key Words: Bio-Concrete, Carbon Sequestration, Carbonation, Industry, Impact

Introduction

Today, climate change is a global crisis affecting everybody and everything on Earth. The most significant contributor to climate change is the anthropogenic emission of greenhouse gases. Carbon dioxide (CO_2) is a greenhouse gas that influences the surface temperature of the earth (Lacis, 2010). Biologists and like researchers have utilized ice core data in the Antarctic to develop a record of atmospheric CO_2 concentrations that dates back hundreds of thousands of years (Barnola, 1987). The 5th report of the Intergovernmental Report on Climate Change (IPCC) analyzed this ice-core data and found that atmospheric CO_2 concentrations are unprecedentedly higher today than they have been in the last 800,000 years (Stocker, 2013). More specifically, in the two hundred years between 1750 and 1950, atmospheric CO_2 concentrations increased from 270 ppm to 310 ppm (US-EPA, 2005). In the following 50 years, atmospheric CO2 has increased to 375 ppm (Figure 1). This significant increase of CO_2 in the atmosphere is a serious environmental issue. Biological springs are starting earlier, and winters are being delayed because of warming. As a result, there is a longer green-cover season that is further affecting climate change, ecological processes, agriculture, forestry, global economy and human health (Penuelas et al., 2009). A literature review published in 2005 claims that the anthropogenic climate change of the past 30 years has played a part in the deaths of over 150,000 people annually. The data analyzed in the review exibit high correlation between climate change and increased cardiovascular mortality, respiratory illness, and incidences of infectious disease globally (Patz et al., 2005).

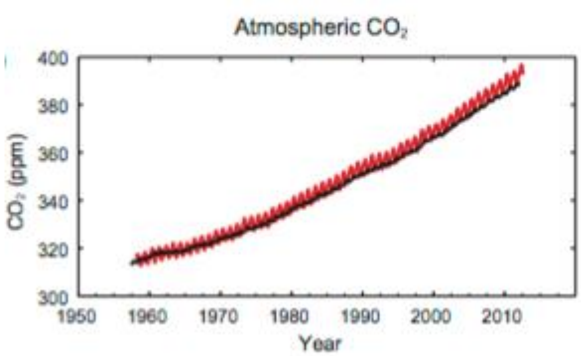


Figure 1: Atmospheric concentration of CO_2 in ppm over time (years) from the 1955 to 2012.

Sinks

One solution to curb the negative effects of CO_2 emissions is carbon sinks. In the past, various naturally occurring CO_2 sequestering sinks have helped combat elevated atmospheric concentration of CO_2. The United Nations Framework Convention on Climate Change defines "sink" as "any process, activity, or mechanism which removes a greenhouse gas… or a precursor to a greenhouse gas from the atmosphere," (UNFCC, 2012). Naturally occurring sinks, include oceans and forests.

Ocean water sequesters atmospheric CO_2 by reacting with CO_2 to rapidly form carbonic acid. Carbonic acid then dissociates into bicarbonate and hydrogen ions, as shown in equation A.

$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H+ +HCO_3-$

Forests sequester atmospheric CO_2 because they are full of photosynthetic organisms that absorb CO_2 and convert it into glucose (Adedokun et al, 2013). This reaction is shown in equation B.

B. $(6)CO_2 + (6)H_2O \rightarrow C_6H_{12}O_6 + (6)O_2$

Historically, naturally occurring sinks have been assumed to be large enough and quick enough to counteract anthropogenic CO_2 emissions, and render them negligible (Bolin 1960). However, at current, unprecedented levels of CO_2, this is no longer the case, and the natural carbon sinks are both declining, and becoming less effective.

Loss of Natural Sinks

The National Center for Atmospheric Research has conducted research showing that as atmospheric concentration of CO_2 increases, so does warming due to the greenhouse effect. Warming reduces the magnitude of the ocean carbon sink by both reducing the solubility of CO_2 across the air-sea interface, and increases the atmospheric partial pressure of CO_2 (Inez et al, 2005). The combination of these two factors dramatically reduces the effectiveness of the oceanic CO_2 sink. The ocean is no longer sequestering CO_2 at a sustainable rate, and as a result anthropogenic emissions are accumulating in the atmosphere (Raven et al, 1999).

Increasing rates of deforestation reduce the potential of forests to sequester anthropogenic CO_2 by killing the organisms responsible for sequestration. Before 1975, a total of only 3,000,000 hectares of the Brazilian Amazon had been cleared (Moran, 1993). In the five years following, deforestation rates increased by a factor of four, to a total of 12,500,000 hectares by 1980 (Mahar, 1988). Deforestation is not unique to the Amazon rainforest, it is also occurring in forests across the globe. The FAO-UNEP Sustainable Food System Programme recorded and published statistics showing deforestation trends in the Guinea-Congolian rainforests of tropical Africa during the twentieth century (Figure 2). The decrease in forest area is dramatic, and illustrates how humans are limiting the effectiveness of forests as a natural CO_2 sink, by literally reducing the size of forest across the globe (Barnes 1990).

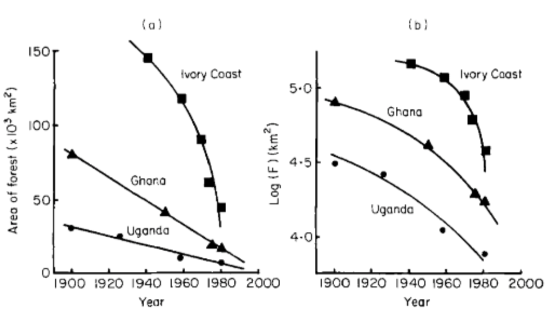


Figure 2: long term trends in forest area ($Km^2 \times 10^3$) as a function of time (years) during the twentieth century. Curves drawn by eye to fit data. (FAO/UNEP, 1981).

The combination of increased anthropogenic CO_2 emission, deforestation, and less effective oceanic carbon sinks have positive feedback on atmospheric concentration of CO_2. In the past 50 years, the annual fraction of CO_2

emissions that remain in the atmosphere has likely increased, from about 40% to 45% (Le Quere, 2009). The upward trend of residual CO_2 concentration corresponds to the decrease in uptake of CO_2 by natural carbon sinks in response to climate change and variability. In other words, natural carbon sinks are becoming less effective as more CO_2 accumulates in the atmosphere, and the cycle is predicted to continue (Le Quere, 2009).

Additional Sources of CO_2 Emissions

One of the larger sources of anthropogenic CO_2 emissions into the atmosphere is the manufacture of cement, the main ingredient in concrete, which accounts for around 5% of global carbon dioxide emissions (Rubenstein, 2012). Additionally, cement production is growing by 2.5% annually, and is expected to rise from 2.55 billion tons in 2006 to 3.7-4.4 billion tons by 2050 (Rubenstein, 2012). With this increase in production will come an increase in CO_2 emissions that we have already begun to observe (Figure 3). There is however, a possibility to combat the negative effects of cement production by turning the concrete it produces into a new kind of large scale carbon sequestering sink.

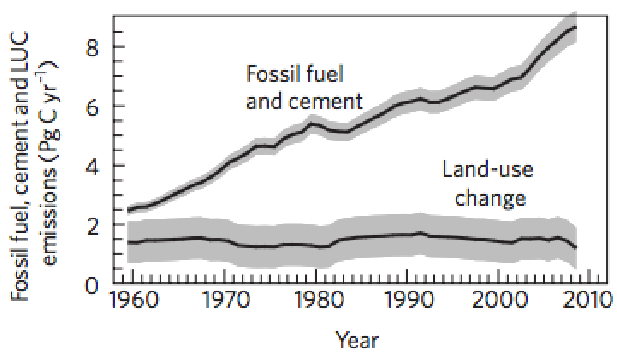


Figure 3: Fossil fuel, cement and LUC emissions from 1960-2010 (Le Quere, 2009)

A solution to the issue of ineffective carbon sinks due to increased CO_2 emissions is man-made sinks. CO_2 sequestering bio concrete is a potential man-made carbon sink that could reduce the carbon saturation of the naturally existing sinks, and the resultant increase in atmospheric CO_2 concentration. The integration of CO_2 sequestration into concrete is made possible by the process of concrete carbonation. At its most basic form, concrete carbonation is a chemical process in which atmospheric CO_2 reacts with calcium hydroxide $(CaOH)_2$ in the concrete to form calcium carbonate ($CaCO_3$) (Lagerblad, 2005). Essentially, this process gives CO_2 sequestering bio concrete the ability to be constantly and consistently removing CO_2 from the atmosphere, leaving calcium carbonate as the primary byproduct. This process takes place over time in the concrete as it is functionally in use.

This paper will explain the biology behind CO_2 sequestering bio concrete that may allow it to act as a carbon sink, reducing the effects of global climate change due to CO_2 emissions.

This paper will also address the industrial utility of CO_2 sequestering concrete. It is important to consider the value of CO_2 sequestering concrete in the construction industry outside of reducing CO_2 emissions such as its strength and cost compared to other traditional concrete varieties. Several tangible applications of this concrete will also be explored to help visualize its potential for large scale implementation which would be required to create the significant positive environmental impact that is recurrently discussed.

Literature Review

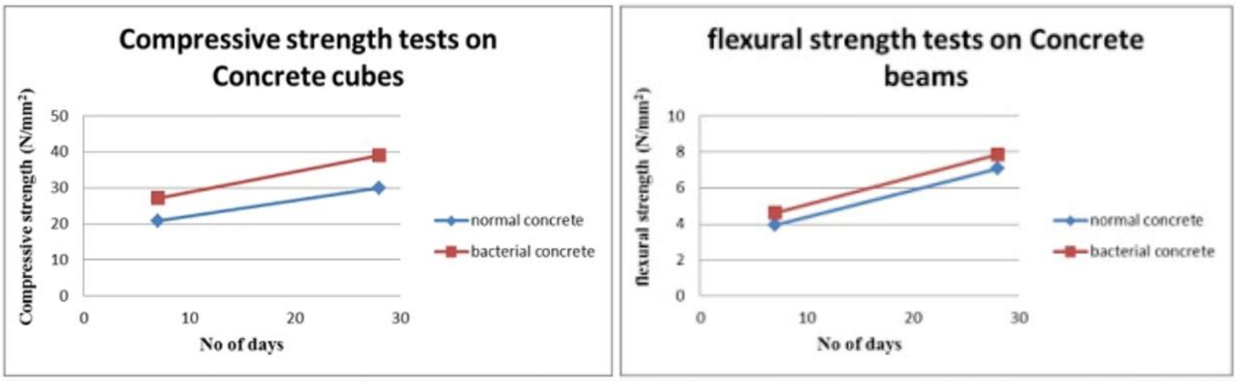
Functionality of Carbon Sequestering Concrete

For a new product like carbon sequestering bio concrete to be adopted by the construction industry on a large scale, it needs to be both functional and economical. This new bio concrete will only be able to remove CO_2 from the atmosphere on a large scale if it is both strong and cost effective enough to appeal to the industry.

Carbon sequestering bio concrete utilizes bacteria from the *Bacillus* genus (Kim, Park, Han, Lee, 2013). These bacteria produce calcium carbonate as they undergo carbonation. Studies done on concrete with calcium carbonate produced from these bacteria have

shown evidence that its compressive and tensile strength may potentially be enhanced. The use of aerobic microorganisms (*Pseudomonas aeruginosa* and *Bacillus pasteurii*), in bio concretes has shown up to an 18% improvement in the compressive strength of cement mortar (S. K. Ramachandran, V. Ramakrishnan, 2001).

Researchers from a 2016 civil engineering seminar tested the compressive and flexural strengths of bio concretes treated with *Bacillus* bacteria. In their experiments, they found that both flexural and compressive strength was greater in the bacillus treated bio concrete. Their results are displayed in the figures below.



SI.NO	DAYS	NORMAL CONCRETE (N/mm^2)	BACTERIAL CONCRETE (N/mm^2)
1	7	20.84	27.09
2	28	29.99	38.98

SI.NO	DAYS	NORMAL CONCRETE (N/mm^2)	BACTERIAL CONCRETE (N/mm^2)
1	7	3.92	4.6
2	28	7.06	7.85

Figure 4: Compressive and flexural strength test data on bio concrete vs standard concrete. (The Civil Engineering Lexicon, 2016).

Additionally, once the pores and the interfacial transition zone of the concrete are filled with microbially-precipitated calcium carbonate, some characteristics of the concrete, such as durability and/or water resistance have been known to increase (Kim, Park, Han, Lee, 2013). These characteristics reduce the amount of work needed to maintain the concrete.

It is difficult to find the exact cost of carbon sequestering bio concrete because it is not being produced commercially just yet, but the cost of bio concrete is higher than the cost of standard concrete. The cost of bacterial concrete is 7 to 28% greater than more conventional forms; however, it can help to reduce the cost of maintenance once installed. This is important because the cost of maintaining standard concrete outweighs the initial financial burden associated with bio concrete installation (Ponraj, 2015). Additionally, if produced on an industrial scale, it is thought that carbon sequestering bio concrete could come down in cost considerably. If the life of the structure can be extended by 30%, the higher cost of the actual concrete would still save a lot of money in the long term. Research is currently focusing on the development of a cheaper version of the bacterial admixture (The Civil Engineering Lexicon, 2016).

Biological Processes

Carbonic Anhydrase (CA)

Carbon dioxide and bicarbonate, are important for the survival of microorganisms because their concentrations (relative to each other) dictate intracellular conditions (Kusian, 2002).   For microorganisms to survive, they must rapidly interconvert CO_2 and HCO_3^- to maintain proper biological processes, such as respiration, pH homeostasis, and ion transport (Ghosal, 2002). The interconversion of the two compounds is represented by the following reversible reaction:

$$CO_2 + H_20 \leftrightarrow H_2CO_3 \leftrightarrow H^{=} + HCO_3$$

(Equation from Karlsson et al, 1998.)

If left up to nature alone, the reaction would occur too slowly for organisms to survive, so it must be catalyzed by an enzyme (Puskas 2000).

Carbonic Anhydrase, is a zinc containing metalloenzyme produced by a wide variety of organisms to catalyze the hydration of CO_2 (Puskas, 2000). The enzyme works because of the nucleophilic attack of the zinc-bound alcohol (OH^-) on the carbon of the CO_2 molecule to produce zinc-bound bicarbonate. The formed bicarbonate is then displaced from zinc by a water molecule:

$$E{\cdot}ZnH_2O \leftrightarrow EZnOH^- + H^+$$

$$E{\cdot}ZnOH^- + CO_2 \leftrightarrow EZnHCO_3^-$$

$$E{\cdot}ZnHCO_3^- + H_2O \leftrightarrow EZnH_2O + HCO_3^-$$

(Equation from Mirjafari et al., 2007.)

In this mechanism, the rate limiting step of the un-catalyzed reaction is skipped. This results in an increased rate of reaction that ranges between 10^4 and 10^6 reactions per second depending on CA isoform, and environmental conditions (Heck, 1994).

Bacterial Production of Carbonic Anhydrase (CA)

Different species of bacteria have evolved to produce and secrete CA into their immediate surrounding environment (Kusian, 2002). An extensive study conducted by The National Environmental Engineering Research Institute (NEERI) in Nagpur, India, screened 102 possible bacteria for the ability to produced stable CA. The research group found that of the 102 strains of bacteria, *Bacillus subtilis* SW3, *Cirobacter freundii* SA3, and *Enterobacter* sp., RS1 showed the highest CA activity throughout the experiment. CA activity was measured in concentration produced. Figure 5 is an image of a plate assay of culture exhibiting *Bacillus subtilis* CA activity (shown in yellow around the bacterial colony). A Western Blot analysis was then conducted to confirm the presence of CA in these experimental cultures (Figure 6)

Western Blot analysis is used to isolate the specific amino acid sequence of a given protein, mark it so that it detectable, and then separate it from other proteins based on size (Mahmood, 2012). The western blot analysis run by the NEERI on the CA produced by *Bacillus subtilis*, compared the enzyme to isolated *E. coli* CA. The results illustrate that CA is a commonly produced enzyme across more than one family of bacteria, and that *Bacillus subtilis* produces CA.

Figure 5: Culture of *Bacillus subtilis*, yellow highlights show CA production

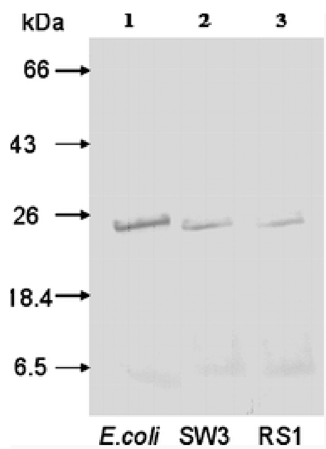


Figure 6: Western Blot analysis of CA protein of *Bacillus subtilis* SW3, *Enterobacter* sp., RS1, and *E.coli*

CO_2 sequestration by CA

CA converts CO_2 to carbonic acid, which quickly dissociates into bicarbonate (HCO_3^-). In this regard, CA sequesters CO_2 by converting it into HCO_3^-. However, HCO_3^- possesses a negative charge and unless stabilized by another reaction, will quickly convert back into CO_2. A study conducted by Kuhad et al., investigated the effects of different metal ion concentrations on CA. It was discovered that CA is strongly inhibited by Hg^{2+}, Pb^{2+}, Ar^{3+}, and EDTA (Kuhad, 2006). These findings prompted biological scientists at the University Jabalpur, India to investigate the effects of other ions on CA. They found that CA activity was not affected by Ca^{2+}, Mg^{2+}, K^{+}, or Na^{2+} and that the enzyme might even perform optimally in the presence of different salts (Sharma, 2009).

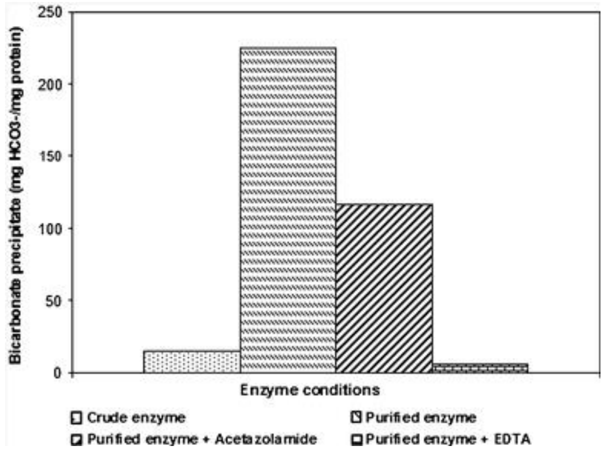


Figure 7: Graphical representation of the volume of bicarbonate deposited in the form of $CaCO_3$ when CA is added to different reaction mixtures (Ramanan, 2009).

This data shows that when CA is added to a reaction mixture saturated with calcium chloride ($CaCl_2$), there is significantly higher bicarbonate precipitation. In other words, more CO_2 is fixed in the form of calcium carbonate ($CaCO_3$). So, when bacteria produced CA is exposed to high concentration of calcium salt, more CO_2 is effectively sequestered. The reaction is as follows:

$$CO_2 + H_20 \rightarrow H_2CO_3$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

$$H^+ + HCO_3^- + CaCl_2 \rightarrow CaCO_3 + (2)\ HCl$$

The data also shows that when CA is mixed with compounds that are known CA inhibitors (acetazolamide and EDTA), hardly any bicarbonate is precipitated. Consequentially, limited CO_2 is sequestered. These data indicate the sufficiency and the necessity of CA in the successful sequestration of CO_2 into $CaCO_3$.

Methodology

The objectives of this analytical research are as follows:

- Present carbon sequestering bio concrete to industry professionals as a solution to rising CO_2 emissions from the construction industry
- Speak to industry professionals from three different perspectives in the construction industry to create a well-rounded opinion of this new technology
- Explain the applications of this material and its strength and costs
- Discuss the potential of carbon sequestering bio concrete to be adopted by the construction industry in order to have a positive impact on the environment
- Compare and contrast the viewpoints of the industry professionals to help understand the future of carbon sequestering bio concrete in the construction industry

The methodology for these interviews first required extensive research into carbon sequestering bio concrete before presenting it to industry professionals. It was important to pick each professional from a different background of the construction industry to get a well-rounded opinion. A general contractor superintendent, concrete subcontractor superintendent, and residential contractor were each selected. First, the professionals were given a brief introduction to the product and an explanation of how its strength and costs may affect its ability to be commercially adopted. Next, the professionals provided information they had on this product or similar products and what they thought about their chances of success. The resulting conversation gave an important insight into how industry professionals view the likeliness of carbon sequestering bio concrete becoming a solution to rising CO_2 emissions. These discussions were recorded and summarized into separate sections for each professional.

Industry Interviews

Scott Shelley: Owner, Scott C Shelley Builders

The first professional interviewed was Scott Shelley, who owns and operates a residential construction company, Scott C. Shelley Builders, in Petaluma, CA. Scott said that he had never heard of carbon sequestering bio concrete, which is evidence that there is not widespread knowledge of this product in the residential construction sector. He has however heard of fly ash, which is a replacement for Portland cement. Fly ash is used because it is required on certain green projects because its production releases less CO_2. He thinks that perhaps this concrete could be integrated into the industry if it became required the way that fly ash is. As far as further research in carbon sequestering bio concrete goes, Scott said that this product should certainly be researched more because of how it could impact the environment, but it would take a company that is willing to sacrifice profits for a while in order to benefit the environment. Although this concrete could save costs in the long run due to its improved strength and healing properties, Scott asserted that in his industry, people are more interested in saving money upfront than in the long term. He also said that it's rare that he encounters a client who is willing to spend more money to benefit the environment. He also said that a 7-28% increase in cost is significant on large scale projects, but less so on smaller scale residential projects.

Michael Bianchini: Superintendent, Pacific Structures

Michael Bianchini is a superintendent for Pacific Structures, a commercial concrete subcontractor based in the San Francisco Bay Area. Michael had never heard of carbon sequestering bio concrete before, but he was aware of other CO_2 emission reducing cement products like fly ash. He said that for a commercial concrete subcontractor, the 7-28% cost increase that is currently required to make this bio concrete is too high for it to be adopted without additional incentive. When asked about the improved strength of the carbon sequestering bio concrete, Michael did admit that it could be an incentive for commercial use if it led to a lighter, stronger concrete. This could mean that companies could save money by spending less on cement. He also said that if this strength increase resulted in a concrete that reached a higher strength in less curing time with the ability to speed up the construction schedule, he could see companies becoming interested. Michael also pointed out that one of the higher costs in concrete turns out to be the installation of post tension cables, so if this stronger concrete could cut down on the amount of post tension cables needed then that could be another incentive to use the product. Overall, Michael reinforced the idea that for carbon sequestering bio concrete to be integrated into the construction industry on a large scale, it needs to somehow cut down on upfront labor or material costs.

Garth Herrema: Superintendent, Build Group

Garth Herrema is a superintendent working for Build Group, a general contractor based in San Francisco. Garth had not heard of any carbon sequestering bio concrete products before this conversation, although he was interested in the possibility of this product to make a positive environmental impact when applied on a large scale. Garth does however see a few hurdles in the way of large scale bio concrete use. He did point out though that as more research is done, the price of manufacture will certainly drop as it did with fly ash or solar panels, two other green building technologies. He also noted that in order for a product that is more expensive than the standard to take off, there needs to be a shift in priorities. Currently profit is greatly prioritized over sustainability, but if this began to change, carbon sequestering bio concrete could start to see some popularity. One interesting idea Garth brought up was sponsored advertising in the form of public works. If a federal building used this new concrete for one of their two story walls and painted a mural displaying the technology, people and companies would see the public backing and have something to be excited about. Although these are a few examples of incentivizing using this concrete, Garth also asserted that the most likely way to get bio concrete to take off is to research it down to the tipping point where it becomes cheaper than an alternative such as fly ash which is currently rising in price due to future predicted supply shortages.

Discussion:

It is clear from the interviews that carbon sequestering bio concrete is not a well-known developing product. The consensus from the industry professionals interviewed is that this product is currently not ready to be successfully introduced to the construction industry. It is too expensive at 7-28% higher costs, and unless more research is done proving that it can cut specific costs, companies will not use it. Even at a lower cost, it would still probably require some sort of public push through sustainability regulations or advertising. According to these professionals, the most promising chance for carbon sequestering bio concrete to be used in the construction industry is if it can reduce material costs like cement or post tension cables, or if it can shorten the schedule by being stronger at an earlier date than standard concrete. There is also a chance that this concrete could achieve a higher strength earlier than standard concrete, which would allow for earlier stripping of formboard and a shorter schedule. If this is the case, it could be another significant incentive for adoption. It also seems likely that carbon sequestering bio concrete would be made popular first in the residential sector due to smaller scale cost increases. It is also important to consider whether this material can compete with the prices of other CO_2 emission reducing methods. Fly ash, for example, is a coal combustion product that can be captured, isolated, and used as a concrete additive to increase concrete tensile, flexural, and structural strength (McCraven, 2013). The use of fly ash in concrete production reduces the necessity to make as much Portland cement. Consequentially, less CO2 is being emitted into the atmosphere as a direct result of the decrease in Portland cement production. So, the use of fly ash in cement production has positive environmental impacts. However, to use fly ash in the first place, coal must be combusted, and coal combustion as an energy source is being replaced by more sustainable energy sources (like solar power and wind turbines). Fly ash is not, hereby, a long-term solution to reducing the anthropogenic CO_2 emission caused by cement production. Other methods and technologies must be investigated and soon implemented to further reduce CO_2 emissions in the long term. CO_2 sequestering bio concrete is one potential solution, and it looks like more research will need to be done on the potential cost cutting benefits of this concrete for it to become an industry staple.

Conclusions and Future Research

In summary, carbon sequestering concrete does have the potential to effectively combat the construction industry's CO_2 emissions when implemented on a large scale through its unique carbonation process, however large scale implementation appears to be unlikely in the near future due to the doubt of industry professionals about the new product's cost. The truth is that as long as there is a cheaper option that works, there is no incentive from the industry's perspective to adopt this new product unless government sustainability regulations were applied. There is certainly future research that could make carbon sequestering bio concrete more likely to be used in the construction industry. Because this bio concrete has improved compression and flexural strength, it's possible that less reinforcement would be required. Calculating precisely how much money could be saved upfront because of reduced cement and rebar material and installation costs could make this bio concrete more attractive to potential investors and construction business owners. However, the currently predicted 7-28% total increase in cost required to incorporate CO_2 sequestering bio concrete into the building process is discouragingly ambiguous. If the coast of the bio concrete could be made lower, with a more precise window of predicted price increase, then there would be a higher likelihood of its commercial application.

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