The Commercialization of Low-Carbon Cements through Calcium Silicate Carbonation of Industrial Waste

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Zachary Abruzzese

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Technical Project Team Members
Jacqueline Canning

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

Advisor

Andres Clarens, Civil Engineering

Technical Report

Abstract

Ordinary Portland Cement (OPC) is one of the largest contributors of carbon emissions. Since continued development of society is reliant on the construction and maintenance of infrastructure, cement cannot be phased out of use. This research seeks to find an alternative to cement based on Roman cement chemistry. Roman cements create minerals, such as tobermorite, which provide similar strengths to OPC. These minerals can be created by curing pseudowollastonite (PWOL) at high temperatures in a pressurized carbon dioxide (CO_2) environment. The PWOL is sourced from a phosphate slag, which is used as the binder in concrete mix, with a low-molarity sodium solution as the liquid. The use of these materials will allow for a significant decrease in OPC use. The decrease in OPC use coupled with the carbon absorption properties of the slags allow for the creation of a carbon negative concrete. It was found that OPC and slag work in tandem to increase strength. An additional chemical interaction is seen between the binders, which causes an increase in formation of calcium-aluminate-silicate-hydrate (CASH) – one of the precursors to tobermorite. This reaction is enabled by curing the mix under high temperature and pressure. To achieve carbon negativity, a lower level of OPC was selected. Adaptations in the curing process by removing the pressure and instead adding Na_2CO_3 for internal carbonation increases commercial viability.

Introduction

An issue plaguing the construction world is the use of OPC. OPC manufacturing contributes ~8% of global anthropogenic CO_2 emissions due to decomposition of limestone ($CaCO_3$) during calcination (Plattenberger et al., 2020). As the continued development of society is reliant on the construction and maintenance of infrastructure, cement cannot be phased out of use. Thus a new, carbon friendly building material must be devised or climate change will continue to worsen.

In an effort to reduce the carbon footprint of cement, an alternative method based on Roman cements has been created. Roman cements create minerals like aluminum tobermorite which are known to be more durable than the carbonates in current-day cement (Ahmad, 2017). These minerals can be created by curing pseudowollastonite (PWOL) at high temperatures under a pressurized CO_2 environment. The PWOL is used as the binder in concrete mix, with a low-molarity sodium solution as the liquid. The curing process rearranges the carbon, calcium, hydrogen, aluminum, and silica in PWOL to create CASH and CCSH gels, which will then crystallize to form the minerals found in Roman cements. The process of curing the cement under pressurized CO_2 captures CO_2 within the cement as carbonates. The strengths of the cement made with PWOL is comparable to the strengths of OPC and the removal of limestone as a base material greatly reduces the initial carbon footprint of the cement. Both of these aspects factor into the potential of this material to be a low-carbon alternative to OPC (Plattenberger et al., 2020).

Previous efforts by the research team involved synthesizing PWOL in the lab, however this process is time consuming and energy intensive, meaning that for the concrete to be a large-scale and life-cycle carbon negative material, another PWOL source must be used. A waste slag was found that contains a large concentration of PWOL. The use of this material as a binder is extremely advantageous, as it requires no dollar cost to manufacture or procure and as a result also incurs no carbon emissions. Therefore, the overall product is expected to be carbon negative because PWOL cements sequester CO_2. The efforts in this paper were to create a slag-based cement mix with comparable strength to OPC-based cement mixes.

Methods

Methods developed in the Clarens lab were adapted to this study of phosphorus slag (PS) low carbon cement. This project followed an iterative mix design, experiment, test, analyze, and revise process, with each successive experiment informed by prior results. Our industrial partner provided insights as to manufacturing conditions and constraints. Experimental mixes were designed to increase palatability and ease of adoption for our stakeholders.

Each mix design was tested and analyzed by casting three two-inch cubes, which were cured and then tested. To start the casting process, the mix of binder and aggregate were weighed out, then put into the chosen cement mixer. The correct amount of liquid was then added while the cement was mixing. Each mix was then thoroughly incorporated to ensure proper distribution. During this process cube molds would be prepared, which consisted of bolting together aluminum plates and applying a silicone coating on the internal surfaces to allow for the removal of the cubes. Once the mix and molds were prepared, the mix was placed into the molds which were then placed on a shake table to encourage distribution of the mix through the molds. The cubes were then leveled and the curing process began.

Curing Processes

The curing process used for all cubes is based on previous work by the lab group. The process differs slightly based on the type of cube. In general, cubes were cured for seven days under pressure and heat. The cubes are placed in a pressure vessel, which is then sealed save for one small port through which a pressure line is connected. A small amount of water is added underneath the cubes (the cubes sit above the water line in the vessel), and the vessel is then placed in an oven, which is turned on to 150 degrees Celsius. Before the oven heats up, the pressure line is connected to the open port in the vessel. The pressure line is also connected to a pressurized carbon dioxide tank. Once the vessel is completely sealed and in the oven with the pressure line connected, the carbon dioxide tank is opened and the vessel is pressurized to 40 pounds per square inch (psi) as read on a regulator attached to the tank. The oven is then closed and the temperature and pressure are monitored over the seven day curing period to ensure they remain constant. After 3 days, the cubes have hardened enough within their molds, so they are removed from the molds and re-inserted into the oven for the remaining 4 days. This baseline curing process is referred to as “CO2” under the curing process column in Table 1 of Appendix B. After the 7 day curing period ends, the oven is turned off and the pressure line is disconnected. Disconnecting the pressure line releases the pressurized carbon dioxide in the pressure vessel and after a short time the vessel can be opened. The vessel is opened and allowed to briefly cool until the internal temperature is low enough that a person wearing oven mitts can reach into the vessel to remove the cubes. After the cubes are removed, they sit out for a minimum of 7 days before testing, and all of the equipment is turned off and cleaned in preparation for the next batch.

The process described above pertains to the curing of pure phosphate slag cubes. Small alterations were made to the curing process over the course of the research to study the effects of different curing conditions. Alterations to the original curing process are described below:

OPC Curing

The addition of OPC to the phosphate slag mixes enables the cubes to set without the addition of heat or pressure. Therefore, all cubes with a percentage of OPC in the binder were left out at room temperature and pressure for 24 hours to set. Once 24 hours had passed the cubes were demolded and then placed in the pressure vessel and oven for the seven day curing process. The ability to demold before curing was advantageous for CO_2 diffusion in the cubes as it was now diffusing into the cube on all 6 sides instead of just the top.

Dry/Wet Cure

The wet/dry curing process was one developed during initial PWOL experiments in the lab. It consists of three days of dry cure as described above. After the initial three days the pressure vessel is filled with enough 0.072 M NaOH solution to fully cover the cubes. The vessel is then resealed and placed back into the oven at the same temperature. However, instead of the 40 psi done for dry cure, the pressure in the vessel is increased to 110 psi. This curing process is indicated as “CO2 D/W” under the curing process column in Table 1 of Appendix B.

Internal Carbonation

The internal carbonation curing condition was created to understand if CO_2 pressure was necessary during the curing process, as an at-scale pressure cooker is not financially feasible. The curing process was nearly exactly the same as the dry/wet cure save two important distinctions: the pressure vessel in which the cubes are cured is not pressurized with CO_2 (instead only steam) and the solution used for the four-day wet cure consists of 7.73 g of Na_2CO_3 dissolved in 3 L of DI water. This curing process is indicated as “0P D/W” under the curing process column in Table 1 of Appendix B.

Hydraulic

Hydraulic cure was used in this project to replicate traditional OPC curing methods, it was used as a baseline curing method to understand the level of reaction seen in the phosphate slag. It consists of submerging demolded cubes in water at room temperature and pressure for seven days. This curing method was only used when curing OPC cubes as the phosphate-slag is not a hydraulically activated binder and requires a catalyst. This curing process is indicated as “H2O” under the curing process column in Table 1 of Appendix B.

Testing and Analysis

To evaluate the success of the concrete the following tests were conducted: compressive strength, thermogravimetric analysis (TGA), x-ray diffraction (XRD), and life-cycle analysis (LCA). Compressive strength is the most important metric for concrete; it provided a baseline to understand if the mix was commercially viable. Mixes that underperformed in this category were not tested further. Mix designs that provided sufficient strength had additional testing performed which included TGA and XRD. These were used to determine the chemical composition of the concrete to discover the source of strength. There were a couple key elements that were desired that contribute greatly to the overall compressive strength. The presence, or absence, of these elements added to understanding of how and why they form. This knowledge was used to further drive experimental plans. TGA was also used to determine the amount of carbon sequestered by a cube. The total sequestration was then entered into the LCA model. LCA was used to evaluate the carbon neutrality of the cement. Large amounts of carbon sequestration does not always indicate carbon neutrality or negativity, as there could be a high carbon cost from energy and transportation.

Results

Introduction

To maintain consistency across mixes, for the OPC replacement study the same general mix design was used. This design consisted of 0.6 kg of binder and 0.36 kg of granite aggregate (a 1.25:0.75 ratio). Water-to-binder ratio (that is, liters of water in a mix divided by kilograms of binder) varied slightly across mixes because the varying amounts of OPC in the cubes required slightly different amounts of water. The water-to-binder ratio for each mix was always between 0.20 and 0.25. The water used in the mixes was not pure deionized (DI) water, but instead was a solution consisting of DI water and sodium hydroxide (NaOH). The NaOH concentration in all OPC replacement mixes was 0.26 M (mol/L).

OPC Replacement Study

Results from prior research showed that the compressive strength of a 2-inch cube casted using exclusively phosphate slags as the binder is 2,900 psi. Varying percentages of the phosphate slag binder were replaced with OPC. Replacement values of 20%, 10%, and 5% were used. The graph in Figure 1 shows the compressive strengths obtained from 2-inch cubes with these different OPC contents, as well as the control pure phosphate slag cube. As was expected, the cubes with higher percentages of OPC had higher compressive strengths. The magnitude of these strengths, however, was unexpectedly large. The 20% OPC replacement cubes had an average compressive strength of 8,976 psi, about three times the value of pure phosphate slag cubes.

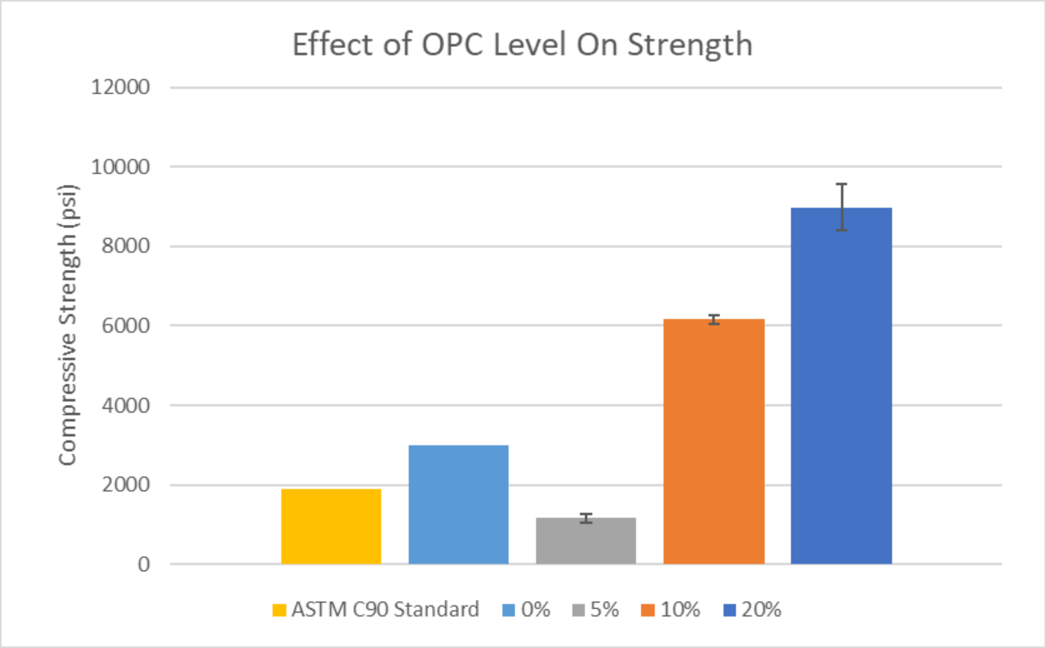
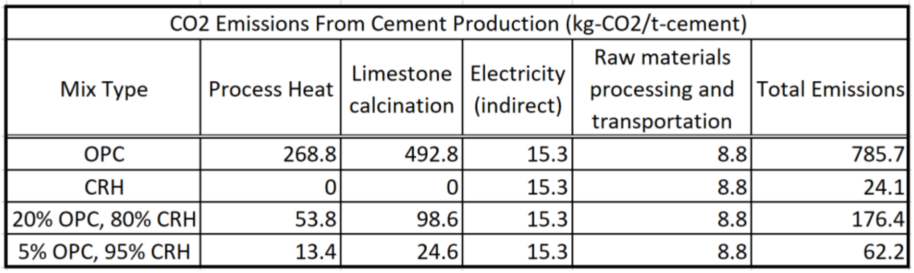


Figure 1

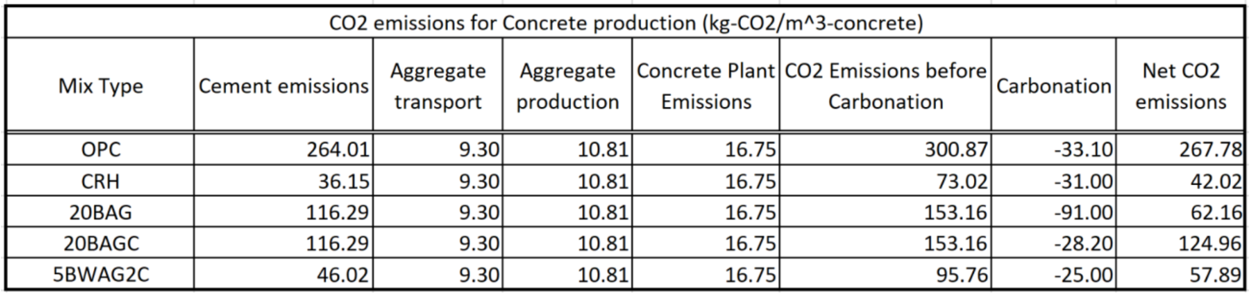
There was a discrepancy in curing conditions between the pure phosphate slag cubes and the OPC-replaced cubes due to the inherent properties of the materials. Phosphate slag requires heat and CO_2 to solidify enough so that the cube can be removed from its mold. However, even the 5% OPC replacement cubes were able to set and be removed from their molds after 24 hours of sitting out at room temperature. The pure phosphate cubes, therefore, were cured (as described above) in their molds for 3 days, then removed from the molds, and then cured for 4 more days. The OPC cubes, however, sat at room temperature for 24 hours, were removed from the molds, and then were cured for 7 days in the conditions described above.

The OPC replacement study conducted requires creating a balance between the strength of the mix and the carbon neutrality of the mix. The 20% OPC mix is shown in Table 2 as 20BAG, it significantly decreased the carbon expense of a typical OPC precast block. However, there is still a carbon cost to the block, especially when compared to the pure slag precast block.



CO2 Emissions From Cement Production (kg-CO2/t-cement)					
Mix Type	Process Heat	Limestone calcination	Electricity (indirect)	Raw materials processing and transportation	Total Emissions
OPC	268.8	492.8	15.3	8.8	785.7
CRH	0	0	15.3	8.8	24.1
20% OPC, 80% CRH	53.8	98.6	15.3	8.8	176.4
5% OPC, 95% CRH	13.4	24.6	15.3	8.8	62.2

Table 1



CO2 emissions for Concrete production (kg-CO2/m^3-concrete)							
Mix Type	Cement emissions	Aggregate transport	Aggregate production	Concrete Plant Emissions	CO2 Emissions before Carbonation	Carbonation	Net CO2 emissions
OPC	264.01	9.30	10.81	16.75	300.87	-33.10	267.78
CRH	36.15	9.30	10.81	16.75	73.02	-31.00	42.02
20BAG	116.29	9.30	10.81	16.75	153.16	-91.00	62.16
20BAGC	116.29	9.30	10.81	16.75	153.16	-28.20	124.96
5BWAG2C	46.02	9.30	10.81	16.75	95.76	-25.00	57.89

Table 2

Curing Conditions

Using the results from the initial replacement study, more research was conducted to try to understand the mechanisms at work within the cubes as well as to try to optimize the mix design for commercial use. These experiments were conducted, due to time and financial constraints, on the 20% and 5% replacement mixes.

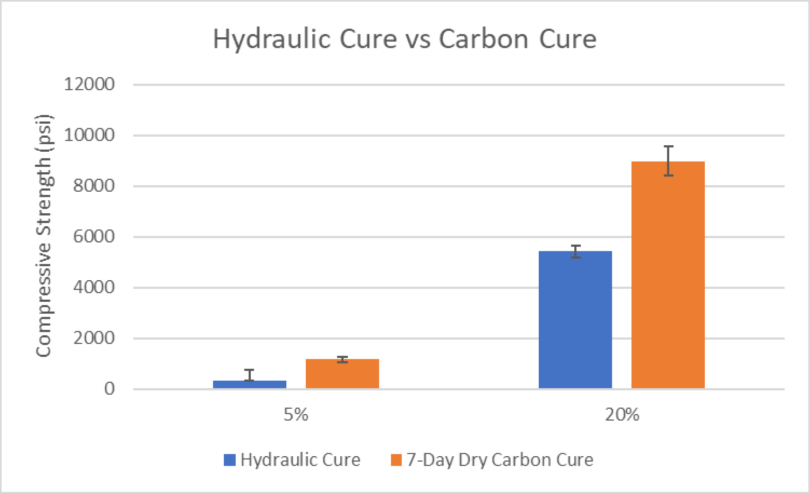


Figure 2

The first of these experiments was intended to illustrate the effects of the pressurized curing method in comparison to traditional hydraulic curing. As seen in Figure 2, the hydraulic curing technique resulted in consistently and significantly lower compressive strengths. The data for the 5% OPC cubes was unreliable, however, as upon insertion of the cubes into the water, two of the three cubes disintegrated. It is unclear what caused two of the cubes to break and not the third, however, the compressive strength is decidedly lower than that of the cubes under the pressurized curing condition.

The second of these experiments consisted of observing how the compressive strength of the cubes changed when exposed to the "dry/wet cure" curing method described above. The graph below (Figure 3) shows the comparison between the dry/wet cure method and the dry cure method.

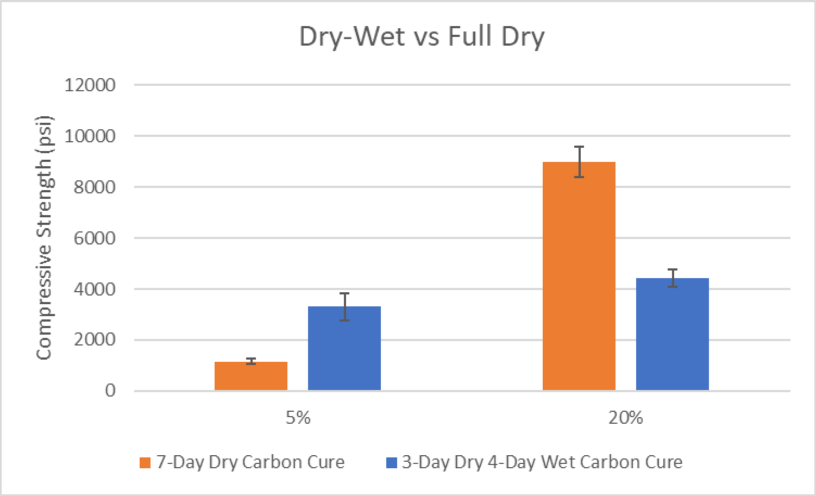


Figure 3

The third and final of these experiments attempted to better adapt the mix design for commercial use by eliminating the need for CO_2 pressure. Instead of using pressure to carbonate the cubes, carbonation would occur from within the cube through the use of sodium carbonate. An Na_2CO_3 solution was used as the mix water with a concentration of 2.03 M instead of the typical NaOH solution. The difference in compressive strength between the pressurized NaOH cubes and the unpressurized Na_2CO_3 cubes was negligible as shown in Figure 4.

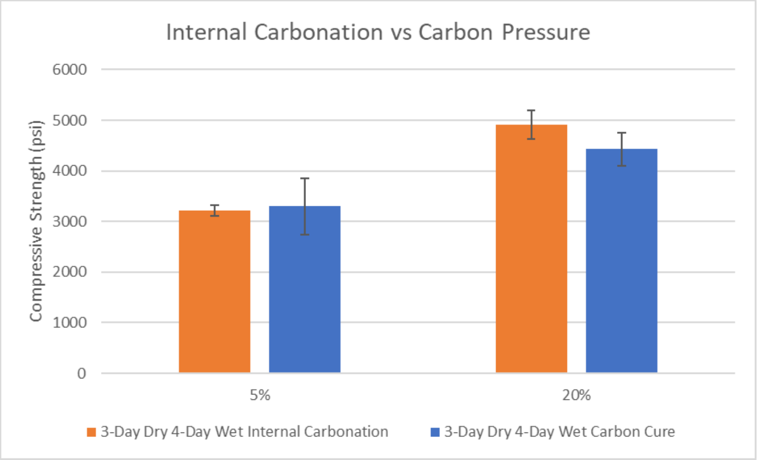


Figure 4

Effect of Alkalinity

In addition to the OPC based replacement studies, a small amount of experiments focused on slag behavior were conducted in parallel. These experiments focused mainly on expanding the knowledge base from which further mixes could be adapted. The first study of this kind was focused on NaOH concentration. Chemistry-based experiments conducted by research group members had shown evidence that increasing sodium concentration increased production of the CASH and CCSH gels, therefore increasing the strength of the mix. Chemistry-based evidence is not a direct correlation to results in the cube-based experiments, however, it is typically a good indicator of the internal interactions in the cube systems. Two mixes were made for this experiment; both mixes had the same binder/aggregate/water ratios as described above and a higher concentration of NaOH. The NaOH concentrations chosen were 0.4M and 0.5M compared to the 0.26M concentration typically used. Results from this experiment are shown in Figure 5, the 0.5M cubes on average performed better than the 0.4M cubes.

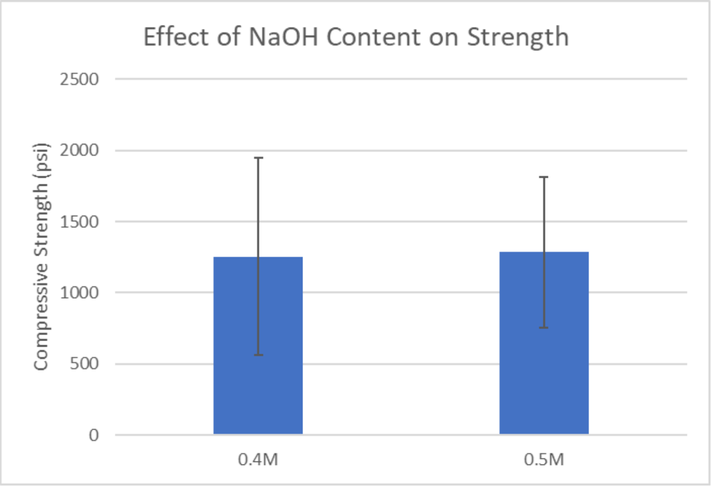


Figure 5

Slag Replacement

Other slags than the phosphate slag in this paper have been found to exhibit abilities to develop minerals seen in roman cements. A replacement study was conducted using blast furnace (BF) slag with the same binder/aggregate/water ratios as described above. Three mixes were developed to observe the performance of the BF slag. The binders in these mixes consisted of: 50% BF and 50% pure PWOL, 100% BF, and 50% PWOL 50% phosphate slag. Due to methodology and reactivity issues, the cubes were malformed at the end of the process, and therefore were not tested.

Discussion

Effect of OPC Inclusion

Additions of OPC to the mixes generally resulted in a large increase in compressive strength. To determine the reason for these large increases in strength, the 20% OPC cubes were cured in a water bath without temperature or pressure. Since these cubes were significantly weaker than the 20% cubes cured at temperature and pressure, it is obvious that the reactions within the slag at temperature and pressure also greatly contribute to the strength of the cube. These two separate processes (OPC hardening and slag reactions) also complement each other. OPC’s reaction with the water in the mix is exothermic, which increases the internal temperature of the cube which increases the reactions from the phosphate slag. Additionally, since OPC contains high amounts of calcium and silica, the presence of a large amount of OPC is conducive to the formation of higher amounts of CCSH and CASH gels. This effect, however, was only observed when large amounts of OPC were present in the mix. As seen in Figure 1, the 5% OPC cubes were an outlier. It is likely, however, that the data from these cubes is unreliable (for a detailed explanation see “Error and Limitations”) because there is a significant decrease in strength from the pure phosphate slag cubes to the 5% OPC cubes, which does not follow the trend shown by the other OPC cubes as seen in Figure 4.

In addition to having the reactions work together, the addition of OPC also allowed for increased CO_2 penetration into the cubes. A problem the team encountered when curing slags for 3 days inside of a mold was that the only route for CO_2 to enter the cube was through the top. If too much CO_2 entered through the top of the cube, a layer of carbonates would form on the surface which would prevent more CO_2 from penetrating into the cube. As CO_2 penetration is necessary for the formation of the strength-giving minerals and material phases, the lack thereof presented a problem for the pure phosphate slag curing method. As the OPC cubes were able to be set and demolded after 24 hours at room temperature, they allowed for greatly increased CO_2 penetration, especially early in the curing process. CO_2 penetration early in the curing process is important because it prevents walls of carbonates from forming on the surface of the cubes which allows the cubes to continuously uptake CO_2 throughout the seven-day curing process.

An issue with the OPC replacement study as a whole was the water-to-binder ratio. A lot of testing was required to determine the optimal water content for the cubes, as the water content had to be higher than that of the pure phosphate slag cubes due to OPC’s reliance on water for its reactions to occur. The optimal water content was determined through many small “ice cube” experiments, where a small version of the mix was casted in an ice cube tray (notated as “Air” under “Curing Condition” in Appendix B, Table 1). The water content had to be adjusted based on the amount of OPC included in the mix, which introduced a confounding variable into the experiment. There is a narrow range of water contents that allow the cube to set and react without drying out and crumbling while not making the cube so wet that water remains in the cube after curing, meaning that experiments could not be performed without changing the water content of the cubes. The change in water content may have affected the compressive strength, but the near-impossibility of keeping the water content the same and having the cubes remain intact forced the research team to change the water content based on the mix’s OPC content.

Another issue with OPC replacement is the role of sodium ions in the mixes. Previous work determined that sodium ions catalyze the phosphate slag reactions that form CCSH and CASH phases, so every mix has included a sodium hydroxide (NaOH) solution instead of pure water. However, the addition of large amounts of Na inhibits the formation of portlandite ($Ca(OH)_2$), from which OPC gets much of its strength. This inhibition can be seen from the substantial drop in strengths from the seven-day dry cured 20% cubes to the three-day dry/four-day wet cured 20% cubes. Because the three/four curing condition requires the addition of a low molarity Na solution for the cubes to sit in, there is significantly more sodium in the system which led to a large drop in strength.

Life Cycle Analysis

Creation of a low carbon based mix requires the use of a life cycle analysis to understand where the carbon emissions are coming from and how much there is in total. As seen in Table 2 above, a pure OPC precast block creates 268 kg of CO_2 per m^3 of concrete. This is a significant amount of carbon emissions, much of which comes from the production of the OPC itself. Removing OPC as a binder, as is done with the phosphate slag cubes, decreases emissions to 42 kg of CO_2 per m^3 of concrete. There is still a carbon cost to the cube as there are manufacturing and transportation emissions that occur despite the use of phosphate slag as a binder. Therefore, the carbon capture ability of the cube is important as it allows the cube to possibly reach zero emissions. As mentioned above, however, adding a small amount of OPC in the binder of the concrete is advantageous for strength, commercialization, and curing ability. For the 20BAG mix, which was cured under the 7-Day Dry Carbon Curing conditions, having 20% of the binder be OPC allowed for an increase in carbon capture. 91 kg of CO_2 per m^3 of concrete was captured, so the final carbon cost of the 20BAG mix was only 62 kg of CO_2 per m^3 of concrete. Typically, having more OPC in the cubes increases the ability of the cube to capture carbon, as seen with the difference between the CRH and the 20BAG mix. However, curing conditions significantly affect the carbon capture abilities as well. Both the 20BAGC and 5BWAG2C, which were cured using internal carbonation, had much lower carbon capture abilities than comparable mix designs. Overall, the mix that is the most commercializable and lowest carbon cost is the 5BWAG2C as it only emits 57 kg of CO_2 per m^3 of concrete.

Error

Concrete production is an inexact science, and as a result there were many errors and inconsistencies present. Errors included leakage of the pressure vessels. The vessels were supposed to remain pressurized to 40 psi with CO_2 for the entirety of the curing process, however the actual pressure would fluctuate substantially. As the research team was unable to constantly monitor the pressure, these fluctuations proved consistent and unavoidable. Steps were taken to minimize the variance in pressure by checking on the pressure periodically and adjusting it as necessary, however the team was unable to consistently keep the vessels correctly pressurized. These pressure fluctuations could have contributed significantly to the carbon uptake of the cubes, as higher pressures of CO_2 will force more CO_2 into the cubes. Therefore, the carbon uptake abilities of the cubes may be understated in the data. Another error introduced in a number of cubes was the lack of a concrete mixer. To mix the concrete prior to pouring it into the molds, the team used a standard KitchenAid stand mixer. The stand mixer was somewhat effective, however it did present problems. For one, it was essential that the mixture be homogeneous and the KitchenAid did not guarantee homogeneity. Especially when small amounts of OPC were added, such as in the 5% cubes, it was difficult to ensure that an equal portion of the OPC was being added to each of the three cubes casted from the mix. Additionally, at one point during the research the KitchenAid broke, which required the team to hand-mix the concrete. Hand-mixing is a poor way to ensure homogeneity and its effects are demonstrated through a lack of reliable data for some mixes. These mixes include the mixes in Figure 5 as well as others that were not tested due to poor creation. In addition to the pressure vessel errors and the KitchenAid errors, there was also error associated with the molds used by the team to shape the concrete into cubes. The molds were made from aluminum, which reacted with the concrete. The presence of aluminum likely contributed to the formation of CASH gels as aluminum is a necessary component of these gels. The phosphate slag did contain small amounts of aluminum due to its status as a waste product, but since the additional aluminum from the molds existed and was not measured, it is difficult to tell if the large amounts of CASH is from the slag, mold, or both. For future experiments, teflon coating will be placed on the inside of the mold to prevent the aluminum from reacting with the cubes.

The ability of the OPC cubes to sit out for 24 hours prior to being demolded was good for increased CO_2 penetration, however it rendered the curing condition inconsistent from previous work. Though it is doubtful that the 24 hours at room temperature and pressure had a large effect on overall performance of the cubes, the OPC cubes were cured for eight days instead of seven. Any increase to curing time will lead to an increase in strength as the reactions within the cube have more time to progress. Additionally, the exothermic reaction from OPC hydration also could have begun to activate some of the slag a day early, which could have again contributed to a slightly elevated strength.

Experiments performed on non-phosphate-based slags were very unreliable. Inconsistencies with water content, temperature, and pressure cause cubes casted with blast furnace slag to fail such that even testing for compressive strength was not necessary. These inconsistencies were due to a lack of familiarity with the slags–for phosphate slags there were two years' worth of testing and optimization that the team could rely on, whereas the blast furnace slags had no prior work.

Limitations

Limitations experienced throughout this research are mainly based on time. Each experiment conducted took at least 3 weeks. Material preparation is typically a multi-day process as ½" rocks must be ground to a fine powder. Each run of the machinery could only produce enough fine powder for at most two mix designs. If casting more than two mixes at a time, more time must be spent on material preparation. There was an upper limit to the amount of mixes that could be cast as well. Only four mixes could be cast at once based on limitations by the machines and materials in the lab. After material preparation, casting and curing took at least a week as almost all of the curing methods were seven days long with a 24 hour setting time before. The casting of cubes also were only able to occur on certain days of the week as there were schedule limitations. After the curing process was completed cubes had to sit out for seven days at room temperature before testing. Therefore there was typically three weeks between mix development and determining the results of the mix. Discussion of the previous results and development of new mix ideas, especially mix designs that relied on previous results were then limited to once a month. Despite best efforts to create the most optimal mix and perform the best lab techniques, there were still situations that occurred that rendered some data unusable

The entire project was also completed within nine months. As this project is for a fourth-year capstone project, only nine months could be committed to the project. The beginning of the project was limited by a knowledge base, as the lab processes and science behind the cement is complex, it took time, especially initially, to make meaningful mixes. With the time limit, there were also only so many mixes that could be cast in total. Therefore each mix had to be thoughtful and final conclusions are limited based on the mixes that were actually cast. There were many more ideas to help implement commercialization that must be tested at a later date.

Commercialization

The overall goal of this project was to create a commercializable and scalable product to enable the use of low carbon cements in industry. Commercializing the mix adds a few limitations to what curing processes are possible. The original curing process of high temperatures and pressures is hard to recreate on a large scale. Therefore some of the efforts in the project were to understand what was important about these curing processes and how to replicate them in other ways. The addition of Na_2CO_3 to the mix, allowing for the removal of pressure, was a large step towards this commercialization goal. Another limitation is that the industry will not want to fully dispose of current practices and materials. The inclusion of a small amount of OPC was a commercial suggestion and aligns with current practices and materials.

Despite limitations on curing procedures, the strengths needed for a commercially viable mix have been achieved. Cinder block strengths are based on the ASTM C90 standard of at least 18 MPa. This strength was achieved by all mixes except for the 5% OPC as the binder cured in water and cured for 7-Days dry under pressure. To fully commercialize the mix, however, the best mix will have to surpass many other material characterization tests. It is important to industry to understand the durability, fire resistance, shear strengths, porosity and many more elements of a mix. Currently, the only standard that has been analyzed is strength. Future moves towards commercialization will have to characterize many more elements of the mix.

Materials used in the mix is also a very important element of commercialization. The materials must be abundant, cost effective, and low in carbon cost. There is not information on how abundant the phosphate slag is. However, commercial partners would not have interest in using the slag as binder if it was not feasible to create product with it. Therefore, it can be assumed that the slag is abundant enough. The other materials in the mix design must be considered as well. Currently, many of the mix designs tested include a certain percentage of OPC, the cubes that have 20% of the binder as OPC, are about 12.5% OPC by weight, which is comparable to the amount of OPC seen in precast blocks today. Therefore, the blocks no longer decrease OPC use, and mixes with a lower percentage of OPC should be developed instead. All of the mix designs also include a sodium source, either NaOH or Na_2CO_3, the chosen sodium source must be cost effective to enable large scale implementation. Future work in improving LCA analysis, removing the need for curing at high temperatures, and material characterization will take the work established in this research to reach a commercializable state.

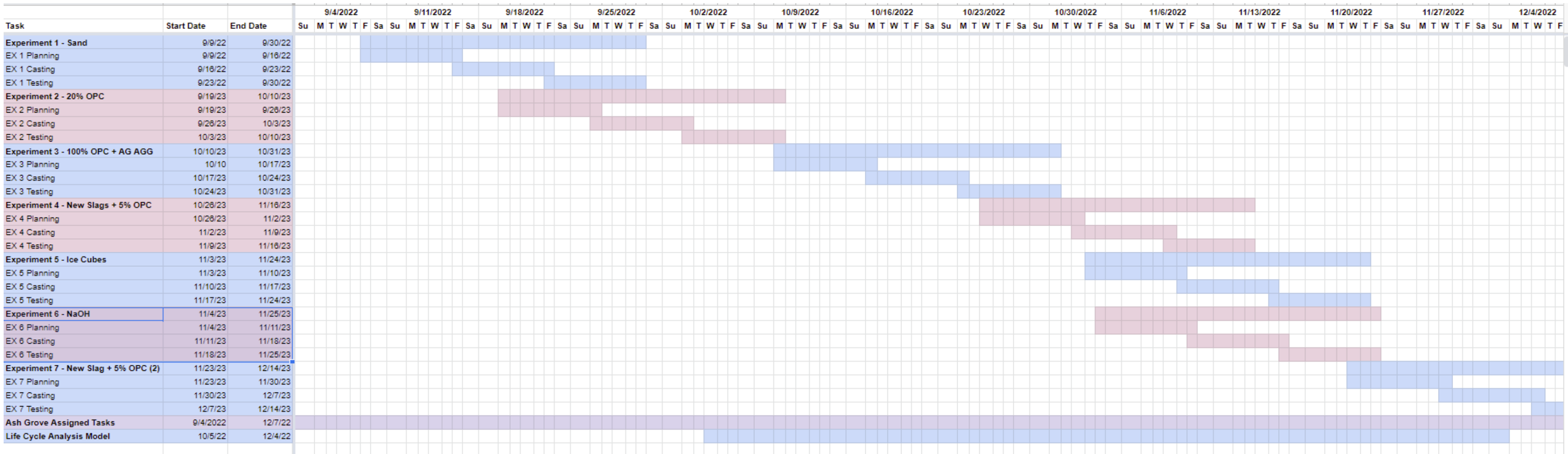
Conclusion

Effectively commercializing a low carbon concrete will require a lot more work, however the steps made currently by the research team demonstrate a promising future. The ability to produce a low carbon building material without the need for a pressure vessel is encouraging due to its alignment with current commercial infrastructure, and the compressive strength data show that the produced concrete is strong enough to be used in cinder blocks.

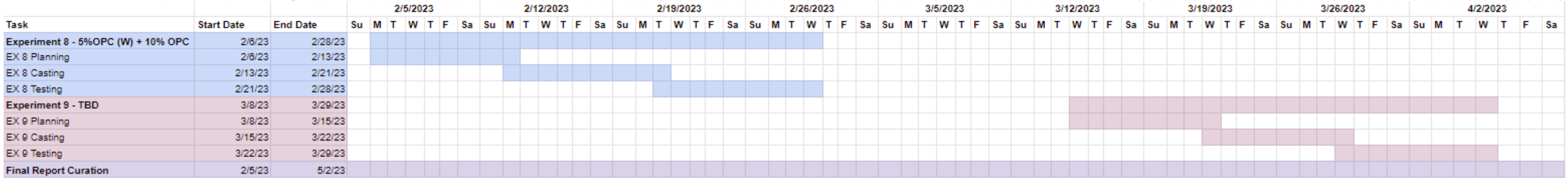
Future work to improve the current design includes gaining a better understanding of the interactions between the slag, the OPC, and the water solution to inform future optimizations and experiments. Additionally, though compressive strength is a necessary standard, there are other requirements (such as durability and fire resistance) that must be considered prior to full commercial use. The availability and location of the phosphate slag waste material may limit the total amount of concrete that can be produced, so a characterization of the available material may be necessary to understand the commercial limitations.

Future work also may include work to increase specifically the commercial viability of the product. Though the sodium carbonate mix prevents the need for constant CO_2 pressure, the current curing condition still requires extremely elevated temperatures, which are carbon intensive and also could be difficult to scale. Steps towards removing the need for such high temperatures could include adding materials to the mix to increase the exothermic reactions present within the cube to heat it from the inside, which could lessen or eliminate the need for high temperatures.

Appendix A: Project Schedule



Task	Start Date	End Date
Experiment 1 - Sand	9/9/22	9/30/22
EX 1 Planning	9/9/22	9/16/22
EX 1 Casting	9/16/22	9/23/22
EX 1 Testing	9/23/22	9/30/22
Experiment 2 - 20% OPC	9/19/23	10/10/23
EX 2 Planning	9/19/23	9/26/23
EX 2 Casting	9/26/23	10/3/23
EX 2 Testing	10/3/23	10/10/23
Experiment 3 - 100% OPC + AG AGG	10/10/23	10/31/23
EX 3 Planning	10/10	10/17/23
EX 3 Casting	10/17/23	10/24/23
EX 3 Testing	10/24/23	10/31/23
Experiment 4 - New Slags + 5% OPC	10/26/23	11/16/23
EX 4 Planning	10/26/23	11/2/23
EX 4 Casting	11/2/23	11/9/23
EX 4 Testing	11/9/23	11/16/23
Experiment 5 - Ice Cubes	11/3/23	11/24/23
EX 5 Planning	11/3/23	11/10/23
EX 5 Casting	11/10/23	11/17/23
EX 5 Testing	11/17/23	11/24/23
Experiment 6 - NaOH	11/4/23	11/25/23
EX 6 Planning	11/4/23	11/11/23
EX 6 Casting	11/11/23	11/18/23
EX 6 Testing	11/18/23	11/25/23
Experiment 7 - New Slag + 5% OPC (2)	11/23/23	12/14/23
EX 7 Planning	11/23/23	11/30/23
EX 7 Casting	11/30/23	12/7/23
EX 7 Testing	12/7/23	12/14/23
Ash Grove Assigned Tasks	9/4/2022	12/7/22
Life Cycle Analysis Model	10/5/22	12/4/22



Task	Start Date	End Date
Experiment 8 - 5%OPC (W) + 10% OPC	2/6/23	2/28/23
EX 8 Planning	2/6/23	2/13/23
EX 8 Casting	2/13/23	2/21/23
EX 8 Testing	2/21/23	2/28/23
Experiment 9 - TBD	3/8/23	3/29/23
EX 9 Planning	3/8/23	3/15/23
EX 9 Casting	3/15/23	3/22/23
EX 9 Testing	3/22/23	3/29/23
Final Report Curation	2/5/23	5/2/23

Appendix B: Sample and Mix Design Data Sheet

The data for all relevant cubes casted are tabulated below in Table 1. Tables 2, 3, and 4 contain the raw mix designs used for each cube. Each mix design created three 2 inch x 2 inch x 2 inch cubes.

Table 1: Sample Data

Sample	Mix Design	% OPC	%BF Slag	% AG Slag	%PWOL	Water to Binder Ratio	Curing Process	Compressive Strength (psi)
1	25SAND			100.00%		0.2	CO2	899
2	25SAND			100.00%		0.2	CO2	856
3	25SAND			100.00%		0.2	CO2	682
1	20BAG	20.00%		80.00%		0.22	CO2	Not Tested
2	20BAG	20.00%		80.00%		0.22	H2O	Not Tested
3	20BAG	20.00%		80.00%		0.22	CO2	9561
4	20BAG	20.00%		80.00%		0.22	CO2	8390
5	20BAG	20.00%		80.00%		0.22	H2O	5184
6	20BAG	20.00%		80.00%		0.22	H2O	5630
4	20BAGP	20.00%		80.00%		0.22	H2O	5656
5	20BAGP	20.00%		80.00%		0.22	H2O	3060
1	20BAGP	20.00%		80.00%		0.22	CO2	Not Tested
2	20BAGP	20.00%		80.00%		0.22	CO2	Not Tested

3	20BAGP	20.00%		80.00%		0.22	CO2	Not Tested
1	SLAGAGG			100.00%		0.2	CO2	Not Tested
2	SLAGAGG			100.00%		0.2	CO2	Not Tested
3	SLAGAGG			100.00%		0.2	CO2	2490
1	POPC	100.00%				0.25	CO2	9260
2	POPC	100.00%				0.25	CO2	10473
3	POPC	100.00%				0.25	H2O	11112
4	POPC	100.00%				0.25	H2O	10768
1	5AG/5PWOL			50.00%	50.00%	0.25	CO2	max 650
2	5AG/5PWOL			50.00%	50.00%	0.25	CO2	max 650
3	5AG/5PWOL			50.00%	50.00%	0.25	CO2	max 650
1	5BAG	5.00%		95.00%		0.2	CO2	Not Tested
2	5BAG	5.00%		95.00%		0.2	CO2	Not Tested
3	5BAG	5.00%		95.00%		0.2	CO2	Not Tested
1	5BF/5PWOL		50.00%		50.00%	0.25	CO2	Not Tested
2	5BF/5PWOL		50.00%		50.00%	0.25	CO2	Not Tested
3	5BF/5PWOL		50.00%		50.00%	0.25	CO2	Not Tested
1	BF		100.00%			0.25	CO2	Not Tested

2	BF		100.00%			0.25	CO2	Not Tested
3	BF		100.00%			0.25	CO2	Not Tested
7	10BAG	10.00%		90.00%		0.2	Air	Not Tested
6	10BAG	10.00%		90.00%		0.2	Air	Not Tested
5	10BWAG	10.00%		90.00%		0.25	Air	Not Tested
6	10BWAG	10.00%		90.00%		0.25	Air	Not Tested
1	5BWAG	5.00%		95.00%		0.25	Air	Not Tested
2	5BWAG	5.00%		95.00%		0.25	Air	Not Tested
3	5BWAG	5.00%		95.00%		0.25	Air	Not Tested
4	5BWAG	5.00%		95.00%		0.25	Air	Not Tested
4	0.4M NaOH			100.00%		0.2	CO2	2100
5	0.4M NaOH			100.00%		0.2	CO2	1150
6	0.4M NaOH			100.00%		0.2	CO2	410
1	0.5M NaOH			100.00%		0.2	CO2	1900
2	0.5M NaOH			100.00%		0.2	CO2	1640
3	0.5M NaOH			100.00%		0.2	CO2	670
4	5AG/5PWOL			50.00%	50.00%	0.25	CO2	Not Tested
5	5AG/5PWOL			50.00%	50.00%	0.25	CO2	Not Tested

6	5AG/5PWOL			50.00%	50.00%	0.25	CO2	Not Tested
1	5BWAG2	5.00%		95.00%		0.25	CO2	Not Tested
2	5BWAG2	5.00%		95.00%		0.25	CO2	1260
3	5BWAG2	5.00%		95.00%		0.25	CO2	1050
1	10BWAG2	10.00%		90.00%		0.25	CO2	5989
2	10BWAG2	10.00%		90.00%		0.25	CO2	6254
3	10BWAG2	10.00%		90.00%		0.25	CO2	6234
1	5BWAG2	5.00%		95.00%		0.25	CO2 D/W	3744
2	5BWAG2	5.00%		95.00%		0.25	CO2 D/W	3618
3	5BWAG2	5.00%		95.00%		0.25	CO2 D/W	2524
1	20BAG	20.00%		80.00%		0.22	CO2 D/W	4521
2	20BAG	20.00%		80.00%		0.22	CO2 D/W	3991
3	20BAG	20.00%		80.00%		0.22	CO2 D/W	4768
1	20BAGC	20.00%		80.00%		0.25	0P D/W	4991
2	20BAGC	20.00%		80.00%		0.25	0P D/W	5210
3	20BAGC	20.00%		80.00%		0.25	0P D/W	4526
1	5BWAG2	5.00%		95.00%		0.25	H2O	Not Tested
2	5BWAG2	5.00%		95.00%		0.25	H2O	Not Tested

3	5BWAG2	5.00%		95.00%		0.25	H2O	939
1	5BWAG2C	5.00%		95.00%		0.25	0P D/W	3063
2	5BWAG2C	5.00%		95.00%		0.25	0P D/W	3295
3	5BWAG2C	5.00%		95.00%		0.25	0P D/W	3270

Table 2: OPC Mix Designs

Mix Type	% OPC	% Phosphate Slag	Binder (kg)	Aggregate (kg)	Water to Binder Ratio	NaOH (M)	Na_2CO_3 (M)
5BWAG2	5.00%	95.00%	0.6	0.36	0.25	0.26	
5BWAG2C	5.00%	95.00%	0.6	0.36	0.25		2.03
10BWAG2	10.00%	90.00%	0.6	0.36	0.25	0.26	
20BAG	20.00%	80.00%	0.6	0.36	0.22	0.26	
20BAGC	20.00%	80.00%	0.6	0.36	0.25		2.03
POPC	100.00%	0%	0.6	0.36	0.25	0.26	

Table 3: NaOH Mix Designs

Mix Type	% Phosphate Slag	Binder (kg)	Aggregate (kg)	Water to Binder Ratio	NaOH (M)

0.4M NaOH	100.00%	0.6	0.36	0.2	0.4
0.5M NaOH	100.00%	0.6	0.36	0.2	0.5

Table 4: Slag Replacement Mix Designs

Mix Type	%BF Slag	% Phosphate Slag	%PWOL	Binder (kg)	Aggregate (kg)	Water to Binder Ratio	NaOH (M)
5AG/5PWOL	0%	50.00%	50.00%	0.6	0.36	0.25	0.26
5BF/5PWOL	50.00%	0%	50.00%	0.6	0.36	0.25	0.26
BF	100.00%	0%	0%	0.6	0.36	0.25	0.26

Works Cited

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