Granulated Blast Furnace Slag and its Effects on Concrete Mixes

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This paper explores what place slag, or granulated blast furnace slag, has in our changing environment and evaluates how it compares to Portland cement. The purpose of this research is to discern how slag will be applicable in the future of construction and find what place it will have in concrete mixes. Slag is a Supplementary Cementitious Material (SCM) that is being utilized in more and more concrete applications due to its desirable properties and low environmental impact. Slag also reduces the amount of CO2 released that is produced in manufacturing and placing concrete. In this research, compressive strength of slag replacement mixes are evaluated against the strength of standard Portland cement concrete through compression testing of cylindrical specimens. Mixes in the amount of 10%, 25%, and 50% slag replacement by weight for cement are tested. This research finds that there are many different aspects to slag as a construction material. Most importantly slag takes longer to develop its compressive strength than does cement. Additionally, it is weaker over a standard 28-day testing schedule. This was found to be due to a few factors, mainly the speed of hydration due to the lack of calcium hydroxide.

Key Words: Slag, CO2, Feasibility, Compressive Strength

Introduction

Cement and concrete are the most widely used building material in the world. In fact, cement production now contributes between 5 to 7 percent of annual global CO2 production. The problem is getting worse as the built environment begins to sprawl over more of our world. Producing 1 ton of cement releases nearly 1 ton of CO2 into the atmosphere due to the burning of fuel, and from the breakdown and burning of limestone in a cement kiln. Concrete needs to evolve and change to be more environmentally friendly as well as sustainable. In the future, low carbon cements and SCM’s will be of paramount importance and will be utilized in all sorts of applications. This research will critically evaluate the different aspects of slag and its effects on compressive strength, consolidation, and durability. There are many additional technologies that are being developed in order to mitigate the impact of concrete on our environment. Things like carbon curing technology, alternative production methods, carbon absorbing methods, and more are already being pursued. Unfortunately, none of these things are widely available in the American market yet, and we must reduce the environmental impacts of producing cement as best as possible until some of these aforementioned technologies become available.
However, we can still produce concrete with a much lower carbon footprint than standard Portland cement with the use of SCMs. The most common of these are slag cement and fly ash. Molten slag is sourced from iron blast furnaces, dried, and finely ground to make slag cement. Fly ash is captured from coal-fired generation plants’ exhaust and can be put directly into concrete. It is important to reduce the impact of CO2 in concrete with increasing urbanization, and this research will show some of the benefits and drawbacks that slag has on concrete.

Literature Review

Concrete is nearly everywhere in the built environment. Yet, it is also one of the worst materials for the environment. This is why SCM’s and alternative methods need to be pursued. Slag is defined by ASTM C125 as a “granulated blast-furnace slag that has been ground to cement fineness, with or without additions, and that is a hydraulic cement” (Slag Cement Association, 2021, p. 5). Slag is an SCM and is also a waste material from iron ore production as illustrated in Figure 1. Therefore, slag is classified as a recovered material as opposed to a manufactured one. The blast furnace slag (BFS) that is collected must be transformed into a useable material, which is a simple but time-consuming process. The BFS is quenched with water to form granulated blast furnace slag (GBFS) and is then dewatered and dried before being sent to a grinding facility where the final product is produced (Slag Cement Association, 2021). From there, the slag will be distributed by suppliers to be used in different applications of concrete mixes.

Slag cement mixes were originally disregarded due to their low early strength and price. However, many limitations have been overcome along with huge advances in technology and building materials. Moreover, as George Wang (2016) states, “Some researchers show it to be possible to formulate slag cements, which, contrary to common cement, may be reinforced with natural fibers” (Wang, 2016, pp. 305-337). This can lead slag mixes to have just as high as a compressive strength as their Portland cement counterparts. In fact, “Concrete containing slag cement as a partial cement replacement can have a higher slump and improved particle dispersion compared to concrete mixes without slag cement” (Pansear, 2019, pp. 55-85). Many alternatives for applications of slag cements are being developed and will begin to be implemented as the market allows.
Environment and Feasibility

With concerns mounting in relation to global concentration of CO2 emissions, an alternative or improvement upon the construction practices we have for concrete is inevitable. With increasing urbanization, the global demand for cement could quadruple by the year 2050 (Johnson et al., 2015). Slag is now able to partially replace cement with high rates of success and retain plenty of the compressive strength even at high levels of replacement. Moreover, since slag occurs as a by-product from the iron industry, there are real environmental advantages that come along with it such as recycling of industrial by-products as well as natural resource conservation (Johnson et al., 2015). According to Johnson, (2015) in a study creating lightweight concrete, increasing the amount of slag in the mix could lead to a decrease in compressive strength of the material, yet replacement levels as high as 70% were still able to provide a structural grade. This is a significant finding because with a replacement level of 70%, there was also a reduction in the overall CO2 emissions by about 50%.

There are also instances where GBFS mixes perform better than ordinary Portland cement (OPC) mixes, such as resisting damage from the environment and fire. According to Sanjayan and Collins (2008), when OPC mixes are exposed to critical temperatures they completely break down due to the dehydration of the Calcium Hydroxide in the mix, followed by the rehydration and expansion of Calcium Oxide. This leads to any OPC cylinder that is exposed to critical temperatures to essentially be reduced to dust as they crack and fall apart. However, the same is not true for slag replacement mixes. This is because the reduction of cement in the mix reduces the available amount of Calcium Hydroxide. With very little dehydration from high temperatures, rehydration does not affect slag mixes like they do OPC mixes because they do not increase in volume and crack apart (Sanjayan & Collins, 2008). This is a significant finding because it shows slag mixes, while being better for the environment, can hold up better against extreme heat conditions than Portland cement can on its own. Slag replacement mixes may soon be specified in areas where there is high risk of fire or exposure to extreme heat because it could potentially prevent the breakdown of OPC mixes and therefore prevent loss of property if used in a mindful way.

Properties

Slag, being a substitute for pure cement has similar aspects of durability and strength but is certainly not the same. Research by El-Tawil et al. (2018) shows that mixes with partial replacement of slag results in lower strength in early stages but increased strength at a later age. “This is in accordance with the hydration heat-induced temperature evolution in which the temperature rise is suppressed in line with the degree of slag cement replacement” (El-Tawil et al., 2018). This is alluding to the fact that the more slag replacement there is, the longer the hydration reaction takes due to the smaller amount of available cement. Also found in the El-Tawil et al., (2018) study, the hydration of slag cement is a very slow process because a glassy, less permeable layer forms upon contact with water and restricts the speed of the reaction. This however can be accelerated by using more Portland cement whose hydration process produces the ions that break down the harder, glassy structure. This is a big part of why it takes slag much longer to develop its design strength than cement. Without many hydroxyl ions present to accelerate hydration it simply takes longer for the reaction to take place. This same study purports that the ideal ratio of slag cement is between 25% to 50% given its effect on flowability and strength, finding that in high performance concrete, slag is actually beneficial in the workability of the mix (El-Tawil et al., 2018). Slag in high performance concrete also reduces the maximum temperature rise and increases shrinkage strain. When compared to regular concrete mix there is a negligible difference, and no additional cracking is present or detected in slag cement mixes.
Using mineral additions like slag is becoming more popular within the industry as cement manufacturing plants try to reduce greenhouse gas emissions from producing cement. High rates of cement replacement designs must take into account things like durability and cracking risk. In a study done by Rozière et al. (2012), several studies were conducted with slag and mineral additions and found the following: Drying shrinkage of slag and Portland cement concrete are almost equal to each other, and slag modifies thermal shrinkage due to the lower heat of hydration. Concrete will shrink and crack no matter what. What is interesting is that in mixes that had “slag and mineral additions [less than] or equal to 50% of the volume proportions of the binder, the evolution rate and the amplitude at a long term of the total shrinkage are lower than that of a Portland cement concrete” (Rozière et al., 2012). This could be because there is less calcium hydroxide in the mix to react with, or simply shape and size of the specimens. Moreover, if over 50% slag or mineral additions are used in a mix, the total shrinkage is very similar to that of standard Portland cement concrete and there is no discernable difference. According to the same study, “these different behaviors are principally due to the porous structure of cementitious materials” (Rozière et al., 2012). Used in optimized mixtures, slag can produce a less brittle final product, which is very good for large slabs with spaced out control joints.

Slag reactivity and its strength development relies on a few different parameters including chemical and physical properties, temperature at which it is cured, and mix design and composition. Slag’s chemical composition differs between sources since it is a by-product. Also, differences in processing have the potential to affect the physical properties of slag like the particle size, and a plethora of other factors (Bougara et al., 2018). Many variables can influence the development and properties of slag replacement concrete. With a keen understanding of how these factors impact the material, predictions about the final product and behavior of the concrete can be made. In Bougara et al., (2018)’s study, it was found that with a 30% slag replacement, there was a decrease in bound water, and at 70% slag replacement there was an increase in the amount of bound water. This is logical as the amount of bound water relies upon the exothermic hydration reaction and is a direct process between cement and water.

**Methodology**

In order to discern relative relationships regarding compressive strength and consolidation between slag and cement, I prepared an experiment using concrete test cylinders. Using a control group and a slag test group, I created 6x12 cylinders for each type of mix as follows: control group, 10% slag replacement (figures 5, 12), 25% replacement, 25% replacement with additional water, and 50% replacement. Mix designs were created based off Lehigh Hanson’s slag mixes in which slag is replaced by weight for concrete. All concrete cylinders were created in accordance with ASTM C31-the standard practice for making and curing concrete test specimens in the field. I chose to do the standard break schedule of 7, 14, 21, and 28 days with each respective cylinder. Each break was done in accordance with ASTM C39 - the standard test method for compressive strength of cylindrical concrete specimens. All batches were mixed in the same concrete mixer, which was cleaned out in between batches. This leads to a small discrepancy in actual versus reported values of materials used, but I deemed this acceptable for the experiment because the research executed is comparative in nature.
Data and results

Mix designs for the control group of cylinders is 70 lb. fine aggregate, 90 lb. coarse aggregate, 40 lb. Portland cement, and 18 lb. of water. Mix designs for the slag replacement cylinders replaced cement by weight with slag in the amounts of 10%, 25% +1 lb. water, 25%, and 50%, respectively. Actual measured quantities are as follows:

<table>
<thead>
<tr>
<th>CONTROL MIXES</th>
<th>FINE</th>
<th>COARSE</th>
<th>CEMENT</th>
<th>WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Quantities (LBS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>70</td>
<td>90</td>
<td>40</td>
<td>18.2</td>
</tr>
<tr>
<td>B</td>
<td>69.6</td>
<td>88.8</td>
<td>39.8</td>
<td>18</td>
</tr>
<tr>
<td>C</td>
<td>68.8</td>
<td>91.4</td>
<td>38.8</td>
<td>16.4</td>
</tr>
<tr>
<td>D</td>
<td>68.8</td>
<td>91.2</td>
<td>40</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 1: Control Mix Quantities

<table>
<thead>
<tr>
<th>SLAG MIXES</th>
<th>FINE</th>
<th>COARSE</th>
<th>SLAG</th>
<th>CEMENT</th>
<th>WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATERIAL QUANTITIES (LBS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>70</td>
<td>90</td>
<td>4</td>
<td>36</td>
<td>18.2</td>
</tr>
<tr>
<td>25%*</td>
<td>70.4</td>
<td>93.6</td>
<td>11.2</td>
<td>30.4</td>
<td>19.8</td>
</tr>
<tr>
<td>25%</td>
<td>70.8</td>
<td>90</td>
<td>10</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>50%</td>
<td>69.6</td>
<td>89.8</td>
<td>20.2</td>
<td>21</td>
<td>21.2</td>
</tr>
</tbody>
</table>

Table 2: Slag Replacement Mix Quantities

As these charts show there are 4 different sets of control cylinders, and 4 different types of slag mix cylinders. Control mixes will be formally referred to as A, B, C, and D, and the slag mixes will be referred to as 10%, 25%* (extra water), 25% and 50%. Mix C and D of the control group had slightly less water than they were designed to have, and consolidation was poor in mix B (Figure 11). These cylinders also had no slump and were not very workable. Slag cylinders were more workable overall, (Figure 6) and slump tests were taken for each mix and are as follows:

<table>
<thead>
<tr>
<th>Control Mix Slump (IN.)</th>
<th>Slag Mix Slump (IN.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Mix Slump (IN.)</td>
<td>Slag Mix Slump (IN.)</td>
</tr>
<tr>
<td>A 1.125</td>
<td>10%  2.6</td>
</tr>
<tr>
<td>B 0.625</td>
<td>25%* 3.1</td>
</tr>
<tr>
<td>C 0</td>
<td>25%  1.75</td>
</tr>
<tr>
<td>D 0</td>
<td>50%  2.5</td>
</tr>
</tbody>
</table>

Table 3: Control Slump

Table 4: Slag Slump

As the data shows, the control mix was not as workable as it should have been, and the slag mixes ended up with more water and higher workability. If there were the exact same quantities of water in these mixes, the slag mixes would have still been more workable due to slag being a less effective binder than cement in early stages. Following is the data collected of the compressive strength of the subjects.
Figures 2 and 3 show the increasing compressive strength of the cylinders as they cure over time. As the chosen testing intervals for this study were 7, 14, 21, and 28 days, the nodes on the diagrams show what the cylinder’s compressive strength was exactly that many days after being poured. This data shows that the cylinders in the control group had higher compressive strength than the slag group by between 1246 and 2001 PSI, with the largest difference between the strongest control cylinder (Mix D Figure 9) and the weakest slag cylinder being 2198 PSI. This is a significant difference and shows the slow development of compressive strength in slag replacement mixes. It is a known fact that slag develops its compressive strength slower than cement, but that effect is amplified over a short, standard testing duration.

The strength curve for cylinders C and D in the control group shows large dips in strength at day 21. This was due to poor consolidation of the mixes, and both failed at lower compressive strengths than the control mixes that were well consolidated. However, the slag mixes demonstrated adequate consolidation throughout each batch (Figure 8). The highest percentage slag cylinder, (50%) had an interesting gradient in it. It appeared to be moving farther down the cylinder as it dried more, but it was certainly still wet in parts when it was tested and broken (Figures 7, 10). This could have been
due to a poorly sealed test cylinder but likely had more to do with the composition of the mix. All other slag cylinders performed in similar ways, appearing less dry than the control cylinders, and were therefore weaker. The following graph represents how the slag cylinders compared overall to the average of the Portland cement control cylinders.

As Figure 4 shows, the slag cylinders were weaker in compressive strength than the Portland cement cylinders at each benchmark for the 28-day testing period. As aforementioned, this is due to the temperature evolution of the mix, which has a lower heat of hydration and a slower reaction occurs. The Granulated Blast Furnace Slag used in this study was sourced from Lehigh-Hanson in San Luis Obispo and met all requirements to be used commercially. This study found that over a 28-day duration, slag cylinders do not develop their full strength, and only develop about 80% of the strength that Portland cement concrete will develop in that time.

**Conclusion**

In conclusion, this project was a beneficial learning experience as I was able to directly apply some of the management skills that I have learned in school and work, by supervising the mixing and making of the concrete test cylinders. Granulated blast furnace slag is a suitable material to be used in concrete, but not when early high strength is needed, or extra high compressive strength is needed. So, in most, or many applications that use strictly Portland cement, slag replacement mixes could be used. For every Ton of cement that is saved by using slag, a Ton of CO2 remains unreleased into the atmosphere because it hasn’t been produced by cement production factories. Slag is more environmentally friendly than pure cement and recycles a by-product of the iron production industry, making it a great resource to use.

There are several drawbacks with using slag, the main ones being inconsistency of the material when sourced from different suppliers, and the slow development of compressive strength at early stages. However, slag tends to consolidate very well, and concrete with optimized ratios of slag has less shrinking capacity than Portland cement concrete. The data presented in this paper shows slag as being inferior to cement as far as compressive strength. However, I believe that with a longer test schedule and more cylinders, results could have been very similar between the two groups. Slag mixes may also be reinforced in certain situations with fibers, greatly improving their strength. Slag
is an important material to be using to aid with the preservation of our environment, as well as to create a suitable, longevous product.

**Future Research**

Future research into this topic needs to include a few things; first and foremost, a longer duration of testing needs to be implemented. Slag takes longer to develop its design strength than Portland cement, so short term tests such as the study done here only shows the early stages of how slag will perform. Over the long-term, the slag cylinders may have reached the same strength as the Portland cement. Future research should also include higher percentage slag mixes, such as 70% replacement or even higher, to see the true effects that slag will have on concrete.

**Photos**

![Figure 5: Mixing – Slag 10%](image1.png)

![Figure 6: Slump Test – 50%](image2.png)

![Figure 7: 50% Slag 14-day Gradient](image3.png)

![Figure 8: Well Consolidated Slag 25%*](image4.png)
References


