Understanding the Effects of High Temperature Stress and Weathering on Concrete Strength

William Pomeranke
Senior, Applied Science, Materials and Nanoscience

Faculty Advisor: Dr. Matthew Ray

Abstract

Concrete exists everywhere in our modern world, so there is a need for a deeper understanding of the stresses it undergoes and how these stresses affect its compressive strength. To do this, we have examined three variables that affect strength: (i) exposure to excessive heat, (ii) the ratios of sand, cement, and gravel in the final concrete, and (iii) chemical testing. It was predicted that as the heat that the concrete was exposed to increased its compressive strength would decrease. A correlation was found between increased heat and decreased compressive strength, ratios were developed that were stronger than the base concrete, and finally preliminary results from chemical testing were gathered. The main result from chemical tests was that further and more vigorous testing was required as the results that were generated were not very substantial.

Keywords: concrete, compressive strength, cement, heat stress, weathering

Introduction

Concrete is composed of four materials: cement, rock, sand, and most importantly water. When the cement reacts with the water, it undergoes hydration. During hydration, the major compounds in the cement form chemical bonds with water molecules and form hydrates. The main two hydrates formed during this process are tricalcium silicate and dicalcium silicate; their formation can be seen in equations one and two. These two hydrates contribute to the strength, with the tricalcium silicate contributing to early 7-day strength and the dicalcium silicate contributing to longer time strengths. [1]

These calcium silicates form needlelike growths (Figure 1) that interconnect the aggregates and the cement molecules. All of these needles interlock with each other, and the summation of all of this interlocking force enables the concrete to be incredibly strong and rigid. Evaluating the compressive strength of a concrete sample is a way of testing the strength of these bonds. Things like heating a sample, chemically treating a sample with an acid, and altering the ratios of ingredients can affect these bonds and thus affect the final strength of the concrete.

Equation 1

Tricalcium silicate + Water → Calcium silicate hydrate + Calcium hydroxide + heat

$$2\ Ca_3SiO_5 + 7\ H_2O \rightarrow 3\ CaO{\cdot}2SiO_2{\cdot}4H_2O + 3\ Ca(OH)_2 + 173.6kJ$$

Equation 2

Dicalcium silicate + Water → Calcium silicate hydrate + Calcium hydroxide +heat

$$2\ Ca_2SiO_4 + 5\ H_2O \rightarrow 3\ CaO{\cdot}2SiO_2{\cdot}4H_2O + Ca(OH)_2 + 58.6kJ$$

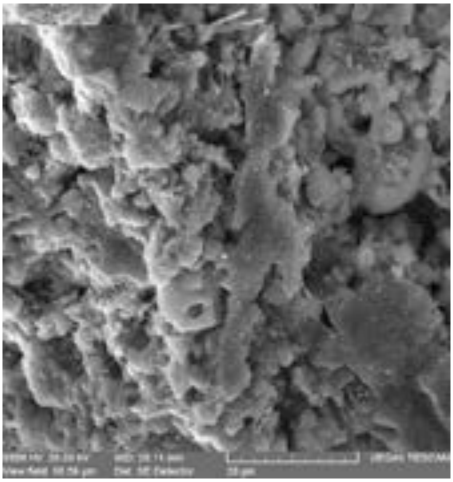


Figure 1: Needlelike Growths.

Purpose

As stated earlier, there is a need to gain a deeper understanding of the various stresses that concrete undergoes when exposed to extreme heat, and to examine the effects of these stresses on the final compressive strength of the concrete. This need is directly demonstrated via disasters such as the Miami Florida condo collapse and the Grenfell Tower fire. Each of these incidents involved chemical and thermal stresses, with the Miami condo collapse probably being caused by water build up over several years and the Grenfell tower fire caused by a faulty fridge-freezer that caught fire, which eventually spread to the aluminum composite cladding on the outside of the building. This spreading to the composite created a chain reaction, and the entire building was quickly engulfed in flame leading to the deaths of 72 people. Incidents such as this are forcing the engineering community to reevaluate how modern buildings are constructed.

Literature Review

As mentioned earlier, concrete is composed of tiny needlelike growths that interlock and give concrete its strength. The most important aspect of this strength is its compressive strength. Compressive strength is how much stress something can take before it fails, and concrete usually has very high compressive strength, hence its prevalent use in buildings. However, on the opposite end of the spectrum, concrete has quite low tensile strength meaning that while concrete can support a lot of weight, it cannot move or shift very much.

The major stresses that effect the compressive strength of concrete are chemical weathering and heat stress. Each of the stresses affect the concrete differently and usually act on different time scales: chemical weathering acts over a much longer time period, whereas heat stress is associated with sudden changes in temperatures, such as fires. Since these two stresses have the most effect on concrete, I will be briefly examining the current state of knowledge related to each stress to give some context to the research in this paper.

Much of the current and past research on concrete and the effect that heat has on it is related to reinforced concrete being used in buildings. Most fires occur in the range of 300 – 800 °C so this is the temperature range that most fire related concrete research focuses on. [3] In this range, there is a significant decrease in the compressive strength of the concrete as well as cracking and, in cases of extreme temperature increase, explosions caused by rapid evaporation of water in the concrete. [4] In order to combat the effects of heat on concrete, various methods exist to model how concrete will behave when exposed to heat, and from these models heat resistant concrete mixtures have been created. [5] Concrete on its own is naturally resistant to fire, and with the addition of things such as lime and the use of calcium aluminate cement the final product is much more resistant to heat damage. [6] Since most research is being done on concrete in the average fire range mentioned above, we set out to examine more extreme temperatures, such as 1000 °C to learn more about the behavior of concrete at these relatively rare temperatures.

Concrete is a very basic material, with the main binding agent, Portland cement, having a pH of 11. This high pH means that concrete can easily react with things such as sulphates and various chlorides. All the various chemical and environmental effects that concrete undergoes can lead to several different types of deterioration such as spalling, disintegration, cracking, and alkali-aggregate reactions. Spalling occurs when pieces of the concrete break off because they are no longer attached to the main structure, and this is usually caused by corrosion or cracking of the reinforcement that is being used to add strength to the concrete. Alkali-Aggregate reactions involve various alkali elements in the concrete reacting with active silica in the various rocks and sand used in cement. This reaction produces a gel like substance that swells and breaks apart the concrete. [7]

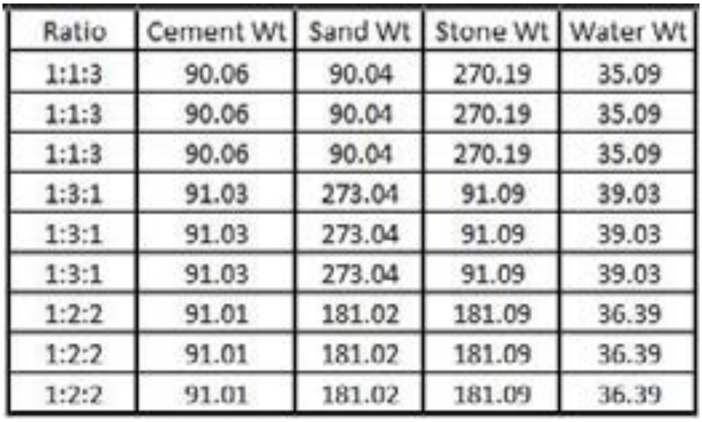
The environment in which the concrete is being used also has a major effect on the behavior of the finished product. An example of this is concrete being used in a sewage treatment plant. In places such as this there are increased levels of sulfates which lead to decreases in both tensile and compressive strength. The sulfates penetrate the concrete and then react with the various elements in the hardened cement paste. [8] In order to further understand concrete weathering we designed an experiment to test various chemicals and their effect on the final concrete.

Experimental Method

This first experiment was designed to test the overall relationship between increased temperature stresses and compressive strength of the sample. To prepare these samples, strict regulations were followed in accordance with the American Society for Testing and Materials (ASTM), and the recipe on the back of a bag of Quikrete 5000 was followed. Quikrete 5000 is a commercially available blend of sand, cement, and gravel that is widely used in small projects such as home patios. Each of the different regulations referred to throughout this paper, such as C31 and C192M, are specific regulations that relate to everything from the way a sample breaks to how to best prepare a sample. Samples were prepared according to ASTM's C31/C31M and C192/C192M to the ratios specified by Quikrete 5000, specifically, 433g of cement to 37g of water per sample. The samples were then cured in a fume hood uncapped for a minimum of two days, then were demolded, and then cured for an additional five days. For the purpose of statistical significance samples were prepared in three sets of three.

Samples were tested and classified in accordance with ASTM's C109/C109M and C39/C39M. The cylinders were then exposed to four different temperatures: 250, 500, 750, and 1000 degrees Celsius. Predictions were then made based off of already existing data from various sources. The samples were put into a Ziploc to contain debris and then crushed in a Carver Hydraulic Press provided by the university to determine their compressive strength. A reading was gathered from the gauge on the press, and the actual compressive strength was determined by dividing the gauge reading by the cross-sectional area of the sample. From here, the data was added to an Excel document, and averages and standard deviations were calculated. Microanalysis was performed using the universities Scanning Electron Microscope (SEM) on the rubble to determine any microstructure differences as well as examine any interesting features. Sample preparation such as sputter coating, which involves coating the outside of a sample with a thin layer of a conductive substance such as gold, was necessary to gather clear images.

The second experiment was designed to develop alternative ratios of cement, sand, stone, and water, with a final goal of creating a mix that either equaled or exceeded the standard Quikrete recipe. Samples with a ratio of 1:1:3, 1:3:1, and 1:2:1, with each number corresponding to a specific amount of either cement, sand, stone, or water. Each of these parts weighed 90g. Table 1 shows the exact amount of each ingredient in each mixture. These samples were prepared in three sets of three and cured uncapped in a fume hood for two days, then were unmolded and cured for an additional five days. Water was added incrementally to each custom recipe until a desirable texture was achieved. Samples were then prepared according to ASTM's C31/C31M and C192/C192M and tested and classified according to ASTM's C109/C109M and C39/C39M. These ASTMs related to specific methods for ensuring an evenly mixed repeatable sample as well as how to properly test aspects such as the final compressive strength of the sample. Samples underwent the same compressive strength testing as the heat-treated samples, data was recorded into an Excel data table, and averages and standard deviations were calculated.



Ratio	Cement Wt	Sand Wt	Stone Wt	Water Wt
1:1:3	90.06	90.04	270.19	35.09
1:1:3	90.06	90.04	270.19	35.09
1:1:3	90.06	90.04	270.19	35.09
1:3:1	91.03	273.04	91.09	39.03
1:3:1	91.03	273.04	91.09	39.03
1:3:1	91.03	273.04	91.09	39.03
1:2:2	91.01	181.02	181.09	36.39
1:2:2	91.01	181.02	181.09	36.39
1:2:2	91.01	181.02	181.09	36.39

Table 1.

A final experiment was designed to test the effects of various chemicals on the compressive strength of concrete by submerging the samples in the selected chemicals. The samples were first prepared in three sets of three according to ASTM's C31/C31M and C192/C192M, using the recommended Quikrete ratio of 433g of cement to 37g of water per sample. After chemical treatment they were tested and classified according to ASTM's C109/C109M and C39/C39M, also of note a deviation in relation to total curing time, specifically samples were cured for nine days total instead of the seven days, as in the previous two experiments. Samples were removed after soaking, rinsed using deionized water and then allowed to air dry for two days. These two drying days account for the increase in cure time. Chemicals were chosen based on our personal preferences as well as what the concrete would react with in accordance with present literature and chemistry.

The chemicals used were a generic cola for testing the effects of phosphoric acid, a generic lemon-lime soda for testing citric acid, acetic acid (commonly known as vinegar), 0.1M HCl, one sample was soaked in water, and a final sample was boiled in water. There was also a time trial element associated with this experiment; specifically, the effects of vinegar were evaluated at two days versus five days, and the effects of 0.1M HCl were evaluated at two days versus five days. After the samples were crushed, a phenolphthalein test was performed on the concrete to determine the penetration depth of the acids being used.

Results

From the data generated from experiment one, we determined a direct relationship between increased heat stress and decreased compressive strength with a sharp drop in strength after 500 °C, which can be seen in Figure 2. We were also noticed interesting microstructure on the samples heated to at least 500 °C. Samples heated to between 500 and 750 °C were smooth, and instead of having needles the samples were covered in what resembled platelets as can be seen in Figure 3. The sample heated to 1000 °C was spongelike in appearance and we hypothesized that the concrete was possibly undergoing re-crystallization. Images of each temperature can be seen in Figure 4. In samples heated to at least 500 °C there was also a change in appearance and sound when struck; specifically, the concrete produced a similar sound to a pot when struck, and the concrete took on a greenish orange tint.

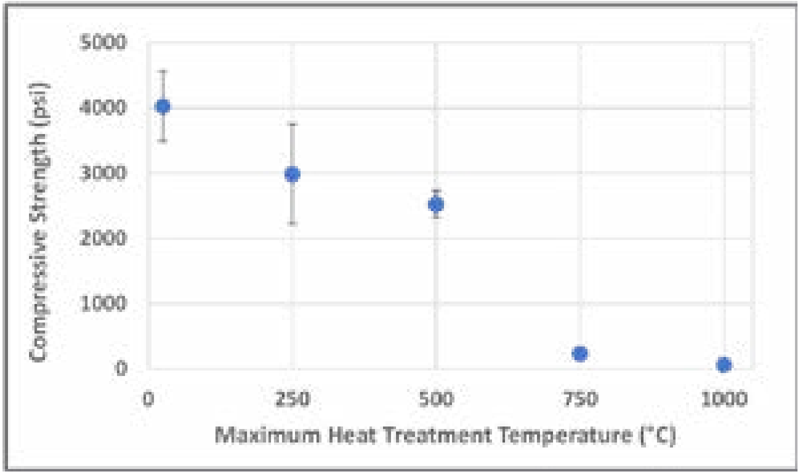


Figure 2: Strength vs Temperature.

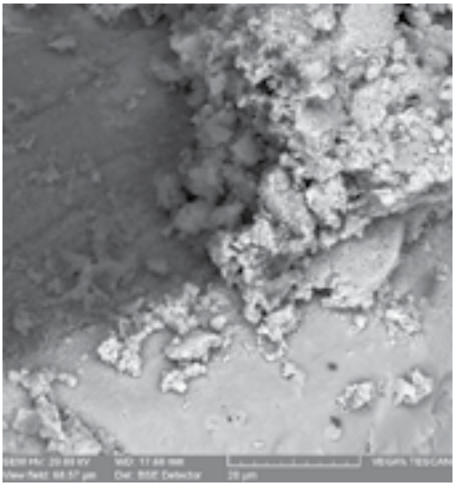


Figure 3: Smooth Platelet Covered Surface.

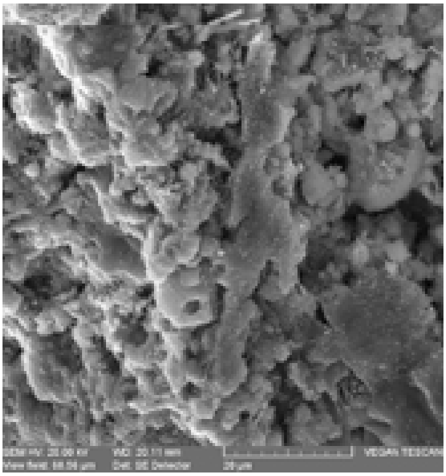


Figure 4a: Crystallization Control Sample.

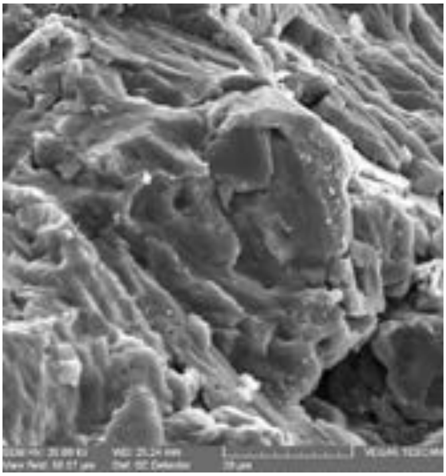


Figure 4b: 250 °C Heat Treatment.

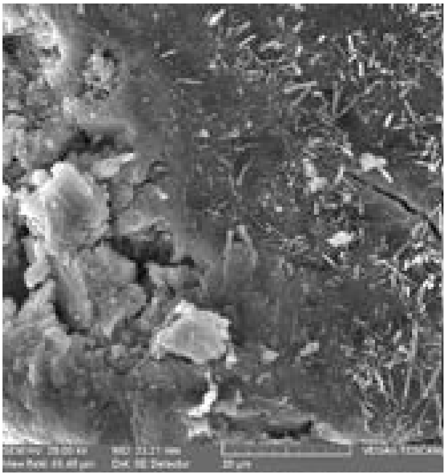


Figure 4c: Unheated Control Sample.

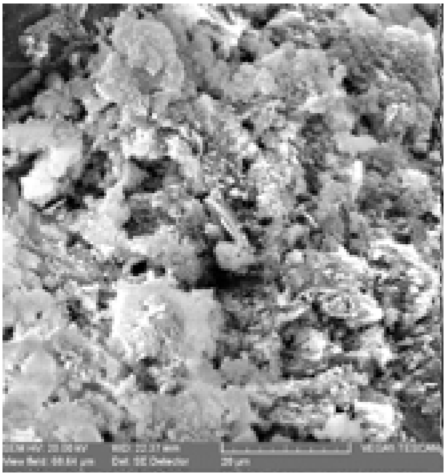


Figure 4d: 500 °C Heat Treatment.

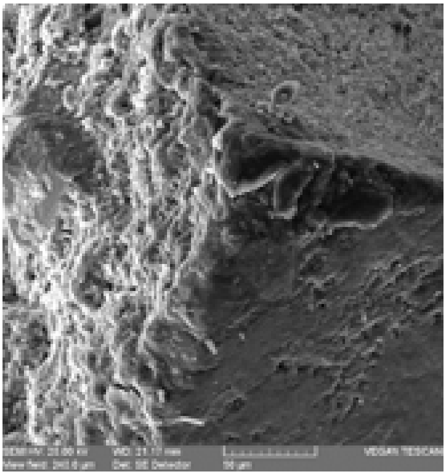


Figure 4e: Untreated Control Sample.

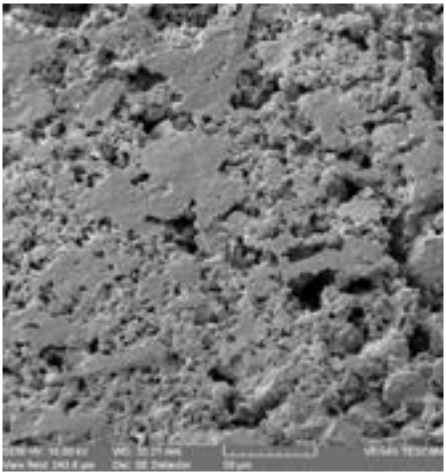


Figure 4f: 750 °C Heat Treatment.

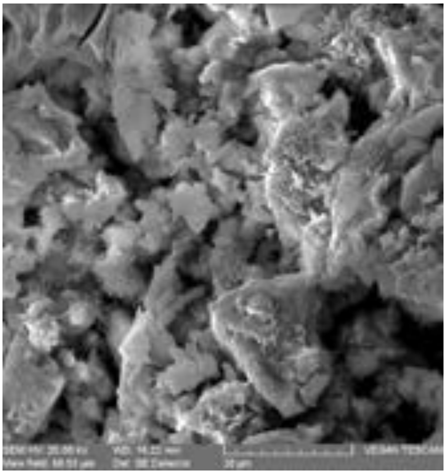


Figure 4g: Untreated Control Sample.

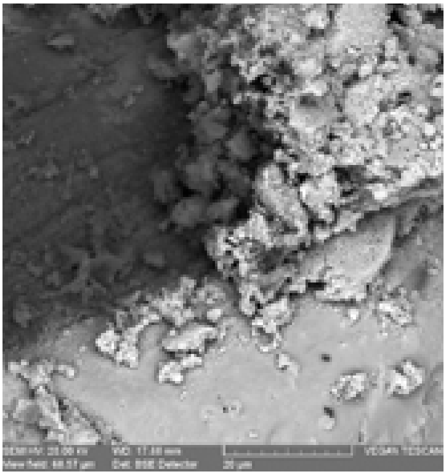


Figure 4h: 1000 °C Heat Treatment.

We were able to develop custom recipe ratios that were either equal to or stronger than the baseline Quikrete 5000 concrete recipe which involved mixing a specific amount of water to a certain amount of premixed Quikrete, in this case the mixture was one pint of water for every 13 pounds of mixture. The compressive strengths can be seen in Figure 5.

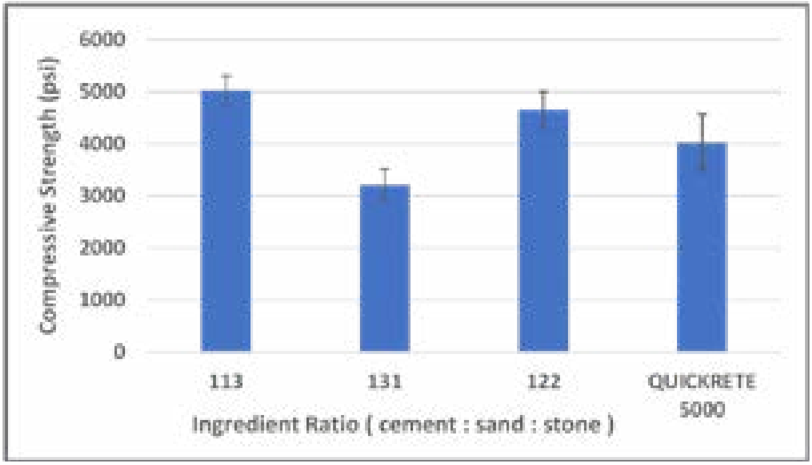


Figure 5: Compressive Strength vs Ingredient Ratio.

For chemical treatment, the results were rather disappointing. There was no penetration on the control or the samples that were soaked or boiled in water; there was a penetration of 2 mm on the sample that soaked in vinegar for five days and a penetration of 1.5 mm on the samples that soaked in vinegar for two days. The remaining cola, lemon-lime, and HCl samples all had a penetration depth of 0.1 mm. Our main conclusion from this test was that more vigorous chemicals were needed for a longer amount of time to have more measurable effects. The chemical testing can be seen in Figure 6 and an example of a phenolphthalein penetration test can be seen in Figure 7.

Figure 6: The Vinegar and HCl Samples After Soaking.

Figure 7: Results of the Phenolphthalein Penetration Test.

Discussion

The results from the heat stress experiment are in line with what we predicted. The samples that were heated to 1000 °C behaved uniquely with the samples having a chalky feel to them and when they were crushed, they turned into dust and rock. These samples were also the hardest to sputter coat for the SEM as the samples were very dry and fragile thus any touching of the outer layer would either cause the sample to entirely fall apart or the outer layer would fall off and the sample would have to be recoated.

The results from the custom ratio experiment were more surprising purely because we did not know what was going to happen going into the experiment. A rough idea of what effect each component would have was known based on how the components react with each other though. The fact that the sample with the most sand was the weakest was not very surprising as there were few big aggregates for the cement to bond to, and the fact that the sample with the most rock was the strongest also makes sense with this logic as there were a lot of aggregate surfaces for the cement to bond to. This experiment was also more difficult than the other two in that we were working with much more hypothetical amounts compared to the other two experiments. The concrete also behaved significantly different due to alterations in the amount of sand, producing a cement that needed much more water and rock, producing a concrete that needed less water but was also harder to work with and also left more air bubbles present in the final concrete.

The chemical test experiment was by far the most surprising experiment because the results were counterintuitive. The vinegar had the greatest penetration depth whereas the 0.1M HCl had almost no penetration. The HCl was expected to have the greatest penetration and it was largely unknown how the rest of the chemicals would. There was also weird behavior during the soaking, there was a gradation present on the vinegar and HCl samples. While this gradation is in itself not unusual and you would expect it to start at the same end on each sample however, the gradation started at different points. The acetic acid sample seemed to react from the bottom up and the HCl sample seemed to react from the top down. By far our biggest take away from the chemical testing was that more vigorous chemicals were needed for a much longer amount of time to get more conclusive results.

Conclusions

The predicted relationship between increased heat stress and decreased compressive strength match the data generated and this conclusion is also backed by real world examples. The results generated from experiment two make sense from the view of how hydration works, and the products generated because we were examining the effects of the different ratios of each component on the final mixture. Finally, the results of the chemical testing were interesting but not substantial and in order to achieve better more conclusive results future research into more vigorous chemical testing is necessary.

Acknowledgements

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