In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Idaho State University, I agree that the Library shall make it freely available for inspection. I further state that permission for extensive copying of my thesis for scholarly purposes may be granted by the Dean of the Graduate School, Dean of my academic division, or by the University Librarian. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature ___________________________________

Date ______________________________

Assessment of Thermal Cycling of Ultra-High-Performance Concrete

by

Michael Elmo Benson

A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in the Department of Nuclear Science and Engineering

Idaho State University

Fall 2022

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Michael Benson find it satisfactory and recommend that it be accepted.

Daniel LaBrier, Ph.D., Major Advisor

Mary Lou Dunzik-Gougar, Committee Member

Mustafa Mashal, Ph.D., Graduate Faculty Representative

Table of Contents

List of Figures

List of Tables

List of Abbreviations

INL – Idaho National Laboratory

ATR – Advanced Test Reactor

UHPC – Ultra-High-Performance Concrete

NPP – Nuclear Power Plant

SMR – Small Modular Reactor

w/c – water to cement ratio

psi – pounds per square inch

ASTM – The American Society for Testing and Materials

ASR – Alkali-Silica Reaction

Abstract

Ultra-High-Performance Concrete (UHPC) is a versatile and robust concrete that is currently used in civil engineering projects. With a new fleet of small modular reactors (SMR) and microreactor concepts being investigated, there is interest in UHPC for applications in the nuclear industry. ANSI/ANS 6.4.2 is a document from the NRC that lays out what physical and chemical properties need to be known about a shielding material before it can be approved for use in nuclear facilities. The goal of this research was to test how UHPC holds up to thermal loads and gamma irradiation with respect to the compressive strength of the concrete.

Three different experiments were designed to test the robustness of the concrete. One test was a combination of heating samples and irradiating them. The other two are testing how the concrete holds up to various types of thermal loads. Four identical box ovens were utilized in testing the concrete. The UHPC mix that was used was LaFarge's Ductal UHPC mix. A generic mix of Portland cement concrete was used as a comparison to the UHPC to provide a baseline for the performance of UHPC.

Before any thermal loading or irradiation, the strength of UHPC was found to be about twice that of normal concrete. After exposure to heat the strength of the UHPC increases up to three to four times stronger than that of traditional concrete. After exposure to radiation and heat the strength of the UHPC was just slightly stronger than its baseline value. There is a possibility of explosive spalling for the UHPC at high temperatures. In fact, during the experiment several samples experienced explosive spalling when the temperature of the oven went above 275 ℃, which suggests a limiting temperature for applications.

It was determined that UHPC is a viable concrete that can be used in nuclear reactors of all sizes and types. Concrete would not experience thermal loads above 250 ℃ during

normal operation in a traditional reactor and the robustness of UHPC compared to the traditional concrete is beneficial.

Keywords: Ultra-High-Performance Concrete, UHPC, Concrete, Thermal Loading, Irradiation

Chapter 1: Introduction

Ultra-High-Performance Concrete (UHPC) is a versatile and unique concrete that is known for its strength and robustness. It is used today in many different applications in various civil engineering applications. It has been used in areas where normal concrete has failed due to corrosion or overuse, such as bridges over bodies of water, as well as architectural concrete.

The goal of this research was to assess the properties of UHPC after exposure to conditions that would be found in nuclear power plants (NPPs) including thermal load and irradiation. With many new small modular reactor (SMR) designs coming out there is an opportunity to evaluate the materials used to construct NPP. Concrete is a major portion of the cost of nuclear power plants, and it is labor intensive to prepare and pour. From the foundation to containment structures and bioshields, concrete is widely used in nuclear facilities. It is popular to use for construction of NPP and other nuclear facilities because of its physical properties, moldability, ease of access for materials, easy manufacturing process, good strength in compression, it is a good radiation shield, and has a relatively low cost. Figure 1 shows how much concrete is used just in the reactor containment building. Because of these factors concrete is used in almost every part of the construction of a nuclear facility. Usually, varying densities of concrete are used for different applications within the NPP.

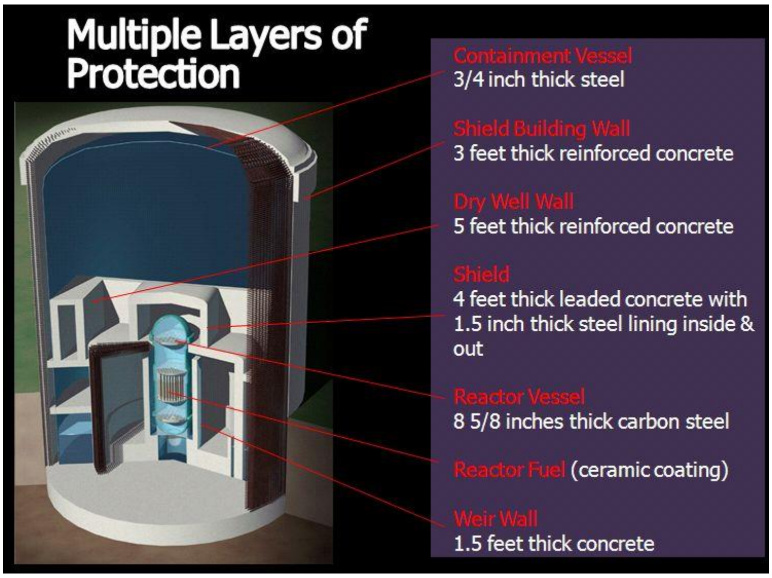


Figure 1 - Diagram of common materials in a reactor containment building

Since the start of construction of the first NPP concrete has been a mainstay in the building of nuclear facilities. There have been minor changes in the type of concrete that is used in building NPP but overall, the concrete has stayed the same.

UHPC has the potential to cut down on the amount of cement needed for nuclear power plants due to its better strength in both tension and compression, resistance to corrosion, and higher density. It is a much denser concrete that holds up better to tensile and compressive loads. It is currently used in bridge deck overlays, in prestressed elements for bridges and as an architectural façade concrete. The prospect of having UHPC available to use in future NPP construction is alluring, but there is a major roadblock to that being able to come to fruition. At this time the NRC has not approved any blends of UHPC for use in the construction of NPP. ANSI/ANS 6.4.2 is a standard that has been written that puts forth the information needed by the NRC for any material to be used as a radiation shield. Since concrete is commonly used as a radiation shield it was decided that the properties laid out in ANSI/ANS 6.4.2 should be researched with respect to UHPC.

The specific properties that were studied in this research are how thermal loads and gamma radiation affect the compressive strength of LaFarge's Dutctal UHPC mix. Since nuclear reactors generate power using heat from nuclear fission the materials used in those structures, like concrete, should be able to handle the thermal loads that are generated from the reactor. Along with the process of fission comes radiation including gamma and neutron radiation to which at least part of the concrete structure will be exposed. Understanding how these conditions can affect UHPC is critical to understanding if UHPC has potential to be used in NPP.

Chapter 2: Literature review

Introduction to Normal Concrete and its use in Nuclear Facilities

Concrete is a mixture of cement, coarse aggregate, fine aggregate, water, and admixtures, if needed (Michael S Mamlouk). Figure 2 shows what wet normal concrete looks like when being poured. The quality of the concrete is dependent on several factors including workmanship, ingredient proportions, chemical composition, curing types, among other things. When mixing concrete, it is important to follow guidelines for mixing. Most premixed concrete mixtures will come with instructions. When mixing concrete from scratch, it is suggested that about 10 % of the water be added, then add 30 % of each ingredient at a time, allowing for the mixture to reach a uniform appearance. When the concrete is poured into molds it needs to either be rodded, according to the American Society for Testing and Materials, ASTM, standards, or vibrated to allow for the concrete to settle and fill the voids in the molds. Rodding is a method where a rod, generally a piece of rebar, is forcibly and repeatedly jammed into cement after the cement has been poured into the mold and before it begins to set. This is done to release entrapped air in the wet cement mix.

Figure 2 - Wet cement being poured

The majority of cement used to in modern concrete is Portland cement. Portland cement is so common that when people reference cement in general it is assumed that is it referring to Portland cement. As is standard in civil engineering, Portland cement is referred to as cement from here forward. If there is a non-Portland cement mixture, then that will be specifically mentioned. The raw materials that make up Portland cement are calcareous materials like limestone, chalk, etc.; argillaceous materials (alumina and silica) like clay, shale, or blast furnace slag; and gypsum. The calcareous and argillaceous materials are crushed, ground, and combined. The samples are then heated in a kiln and then the gypsum is added. This creates a very fine powder, which creates more surface area for better hydration. The major compounds that come out of the raw materials are calcium silicates (C_3S and C_2S), and calcium aluminates (C_3A, C_4AF). These two compounds provide most of the calcium and silica that are needed for the formation of C-S-H which is what makes the cement strong. Minor compounds that may be found in cement that can have strong influences on how the concrete performs are metal oxides (MgO, TiO, MnO, K_2O, Na_2O). The potassium and sodium oxides are of importance because they provide alkalis that react to with silica and cause the disintegration and expansion of cement. This reaction is often called the alkali-silica reaction (ASR). The alkalis often are introduced to the mixture from the gypsum. The gypsum is added to prevent rapid settling and improve strength development. The ASR happens when water leaches into the concrete dissolving the alkalis and calcites and allowing them to form in air voids in the cement.

ASTM C33 is a standard that defines the difference in coarse and fine aggregates and their range of sizes. In a larger project, usually coarse aggregate can be as large as 3 to 4”. It is better to use smooth round coarse aggregate as it improves workability and lowers the amount of water and cement needed. The size and quality of fine and coarse aggregate drive variations in gradation, water content, how much cement is needed, and workability. Larger aggregate needs less water to reach optimal workability, requires less cement, but is harder to work. Finer aggregates allow a better w/c ratio which allows for stronger concrete. There is a balancing act that needs to be done to balance the costs and strength of the concrete needed.

A very crucial part of the concrete is the water that is used in the concrete. The main guideline on water used to mix with concrete is that it should be potable. Acceptable criteria for what types of water can be used are laid out in the standard ASTM C94. Apart from making the concrete workable, water is part of the chemical reaction that gives concrete its strength. This process is called hydration. It is a common misconception that cement gains its strength from drying. When cement dries out via evaporation it means that the concrete is losing water to the air which stops the strength gain. Hydration is the process that takes the hydrogen from water and combines it with the calcium silicates (C_3S (3 CaO • SiO_2) and C_2S) to create C-S-H chains. The hydration process, like most chemical reactions, causes heat which can cause problems in the cement if there is too much heat generated. This process initially moves very quickly, which leads to the initial hardening of the cement, then it slows down and becomes a long-term chemical reaction. The hydration of cement in dams can take decades due to the amount of cement used. The water to cement, w/c, ratio is a the most important property of hydrating cement. A w/c ratio of 0.4 is optimal but may need to be adjusted according to environmental conditions and needed properties of cement, such as the sulfate content in the soil and water as well as temperature range the concrete will be exposed to. It is important to remember that increasing water in the mixture may increase the workability, but it will cause voids which decrease the overall strength and durability, lowers the ability for bonds between layers of concrete and between concrete and rebar, and it increases volume change from wetting and drying.

The final component of concrete mixtures are the admixtures. Admixtures may or may not be needed depending on what properties are needed from the cement. Admixtures do many things and can be classified into 6 major types: air entrainers, water reducers, retarders, hydration controllers, accelerators, and specialty admixtures. Air entrainers increase the amount of air in the concrete via tiny, dispersed air bubbles in the concrete. This helps the concrete when exposed to freezing temperatures as it gives the expanding freezing water a place to expand to. Water reducers improve the mobility of cement particles. It can be used in three different ways. It improves workability with the same w/c ratio or increases the strength at a lower w/c ratio or reduces cost at the same w/c ratio by allowing less water and cement in the mixture. A subset of water reducers are plasticizers or superplasticizers. They can be used to significantly decrease the amount of water needed in the cement. Their downside is that they only last for 30-60 min. This means that they must be added at the job site and the cement needs to be poured quickly. Retarders delay the initial set of the concrete. This increases the set time, which means the concrete remains workable for a longer amount of time. They typically don't delay the final set time by much. Hydration controllers can stop and restart the hydration reaction in cement. This is useful when cement is being hauled long distances. Accelerators decrease the set time. Finally, specialty admixtures can do anything from reducing corrosion to being fungicides (Michael S Mamlouk).

After concrete is mixed and poured according to ASTM standards there are various methods to cure the concrete. Curing of concrete is done after the concrete has set. Some various forms of curing concrete are normal water curing, hot water curing, heated air curing, normal air curing, and electrical curing. Water curing is done to keep the surface wet allowing for the hydration process to have enough water to finish. Continuously cured concrete is considered best because the hydration process is allowed to continue in perpetuity. Concrete is considered continuously cured if it has been immersed in a water bath for 28 days (Michael S Mamlouk). Using hot water promotes hydration and increases pozzolanic activity which lengthen C-S-H chains increasing strength (Gai-Fei Peng) (Jamshaid Sawab). Air curing is a simple way to cure concrete and the most economical as no extra material is needed. Air cured concrete only reaches 50% of the strength of continuously cured concrete (Michael S Mamlouk). Electrical curing can be done by applying an alternating current to the freshly laid concrete, or large electrical blanket is used to heat the slab surface. Curing can be either one or a combination of methods. This is called mono-curing or combined curing.

Introduction to UHPC

UHPC is a useful and versatile concrete due to it being more durable and denser than normal concrete. Its durability can be shown in its impermeability and resistance to corrosion. It utilizes smaller aggregates which creates a higher level of homogeneity which contributes to higher compressive strength and a more ductile behavior. UHPC produces compressive strengths over 125 MPa (18 ksi, or 18,000 psi). Previously strengths above 100 MPa (14,500 psi) were not attainable without some sort of special treatment such as high-pressure curing, heat curing, extensive vibration, special aggregates, or specialty admixtures. The mix that is used in this research includes stainless steel fibers which help increase compressive strength, ductility, and its tensile performance.

UHPC can attain compressive strength over 125 MPa (18,000 psi) (Jamshaid Sawab). The development of UHPC is a relatively new field in concrete. Previously strengths above 100 MPa (14,500 psi) were not attainable without some sort of special treatment such as high-pressure curing, heat curing or extensive vibration. With the development of new materials, the ability to have concrete that stands up to strengths at or above 150 MPa is attainable. UHPC can attain these strengths without extra mixing and curing steps that increase the time needed to pour the cement.

UHPC replaces coarse aggregate with various fine and very fine aggregates such as silica sand, fly ash, silica fume, or other similar materials. These materials act in different ways to aid in increasing the strength of the concrete. Fly ash is the most common pozzolan used in civil engineering. A pozzolan is a material that by itself possesses no cementitious value but when it is finely divided and mixed with calcium hydroxide ($Ca(OH)_2$) it reacts with water and forms compounds that have properties like that of cement. Fly ash is a byproduct of the coal industry, therefore can be obtained easily. It is primarily a silica glass made from silica, alumina, iron oxide, and lime (Michael S Mamlouk). Fly ash increases workability of the cement and extends the hydration process. Silica fume is a byproduct of the production of silicon metal or ferrosilicon alloys. Due to its properties, both chemical and physical, it is a highly reactive pozzolan. When used in cement it increases strength and durability and can increase corrosive resistance. The reason it is so effective as a pozzolan is it is a very fine particle, has a large surface area, and has a high silica (SiO_2) content. Because it increases the amount of water needed and decreases the workability, superplasticizers are recommended when using silica fume (Michael S Mamlouk). Other materials that have been studied for use in UHPC are amang, lead glass and magnetite (Raizal S.M Rashid) (N.M. Azreen).

To increase the ductility and strength of UHPC cement, fibers are added to the mixture. Fiber types that can be used are stainless steel, polypropylene, and polyvinyl alcohol (PVA). The fibers hold the concrete together as cracks form and propagate. The different types of fibers are used for their various physical properties. Stainless steel fibers are a common fiber to use for their strength. Polypropylene and PVA fibers are used because they have a good strength, but they also melt at higher temperatures to allow for the release of free water in the concrete as it begins to evaporate which is supposed to help reduce the vapor pressure in the concrete.

With the pozzolans replacing coarse aggregates in UHPC the grain structure of UHPC is much denser. Figure 3 shows the difference in grain structure of the UHPC vs that of normal cement. The addition of the pozzolans allows for lower w/c ratios and allows for less cement to be used. Silica fume is a very popular pozzolan in UHPC blends which helps increase strength and then when

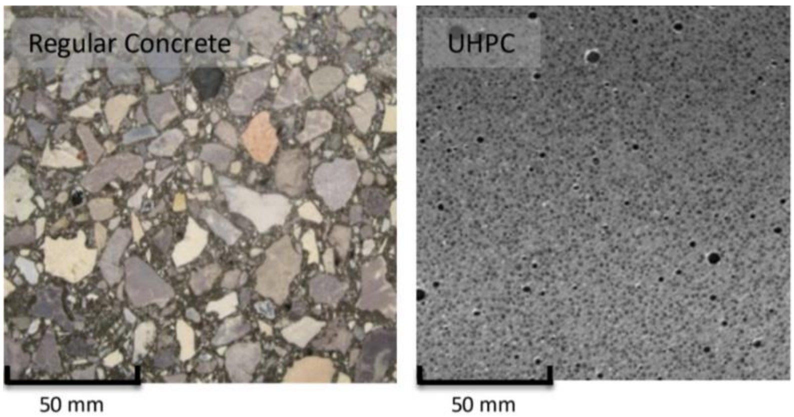


Figure 3 - Comparison of normal concrete and UHPC grain structures

combined with a lower w/c ratio it can be seen where the increased strength of UHPC comes from.

Uses of UHPC in Industry

UHPC is currently used in industry today. It has uses in building bridges with prestressed girders, joint filler for bridge sections, precast waffle panels for bridge decks, as well as many other uses. UHPC can also be utilized in variety of ways, including, field cast, poured, overlayed or even shotcrete. This variety of uses provides additional utility. It is currently more of a novel use concrete.

A specific example of UHPC use is the Chillon viaducts. The Chillon viaduct is a set of two bridges over the east end of Lake Geneva in Switzerland. The viaducts are 1.4 mile long prestressed concrete box girder bridges that carry east and west bound traffic on the A9 highway. When it came time for the deck to be redone damage to the rebar was found. When tests were done there was damage to the concrete from the ASR that compromised the mechanical properties of the concrete. The damage to the rebar and cement was from the amount of water that the cement and rebar was exposed to. It was decided to use fiber reinforced UHPC as a deck material. The UHPC can handle more load as the number of cars using the viaducts has significantly increased, also due to the waterproofing ability of UHPC it will mitigate and avoid any further damage from the water. Also, since the UHPC can cure quicker than normal cement the deck was able to be finished quicker (UHPC Solutions North America).

Some of the downsides to UHPC are the overall cost, the exacting nature of the mixing procedures, and the materials it uses. In general, UHPC has a higher cost than normal concrete. This cost includes increased costs for higher power cement mixers. The mixing procedures for UHPC blends are more rigorous and exact then normal concrete. For example, the procedure for the UHPC mix from Ductal is timed into five well timed steps that take a total of 20 min to mix (LaFarge). This is more precise and time consuming than the process to mix normal concrete. Normal concrete is just adding 1/3 of each ingredient allowing time to mix then adding another 1/3 of each ingredient. Per Ductal, it is suggested that it takes 12 men to mix, cast, and form about 3 m^3 of cement over a 10-hour day. Since UHPC has such a fine grain structure the cost of obtaining the materials is high. For example, silica flour can be as fine as 5 μm. Normal Portland cement grains are on average about 45 μm.

Possible Uses of UHPC in Nuclear Facilities

UHPC has the potential to be extremely useful in nuclear applications. It flows better than normal concrete, is stronger and sets faster, to name a few benefits. This can simplify the construction process for small modular reactors as it removes the need for rebar in containment buildings. With the increased compressive strength, the containment buildings can be more resistant to accident scenarios, and potentially last longer than traditional concrete. The advent of UHPC has the potential to create accident tolerant buildings for both large scale commercial NPP and SMR, further providing improved protection to the public.

Testing how UHPC handles the heat and various forms of radiation that it will be exposed to as a part of a NPP, either a SMR or traditional power plant, is needed to confirm the safety of its use. The concrete should be exposed to heat and radiation loads that are part of the normal operating conditions as well as possible transients that may be experienced as part of accident scenarios.

Mechanical Testing

The strength of the concrete post stressing will be done via compressive strength testing. Destructive testing was chosen because nondestructive hardness tests are cost prohibitive or require multiple tests within a certain area that can lead to issues in accuracy. Compression testing is a standard form of strength testing according to ASTM standards. Figure 4 shows a sample from this research in the compression testing machine. Most samples are in a cube geometry which is outside the ASTM standard. This geometry was chosen due to ease of pouring and testing. The ovens procured for the thermal cycling are 6 x 6 x 8.5”. which limits the size of samples that can be tested. This also eliminates the ability to test for tensile strength.

Figure 4 - Sample being compression tested

Methods of nondestructive testing include the rebound hammer test, penetration resistance test, maturity test, and ultrasonic pulse velocity test (Michael S Mamlouk). The rebound hammer test uses an instrument that holds a mass with a spring. The mass is spring loaded and when released it strikes the surface of the concrete and the rebound is measured on a meter. The higher the rebound the harder the surface of the concrete. There is a correlation for the surface of the concrete to the hardness of the whole mixture. Figure 5 shows a rebound hammer used for concrete testing. This test can be affected by various factors including local vibrations, coarse aggregate being close to the surface, voids just below the surface. Since

Figure 5 - A rebound hammer used to test for concrete hardness

it is impossible to guarantee perfect testing conditions it is suggested that 10 to 12 tests be taken. This testing method is set forth in ASTM C805 Due to the smaller surface are of the samples it is not feasible to get 10 independent readings, also the time to test as many samples as we have is not practical. A penetration resistance test is described in ASTM C803. The test involves 3 probes being shot into the concrete with a special tool and a template plate. The average of these three penetrations is taken and a correlation table consulted to determine the hardness of the concrete. This test is considered more accurate as it tests more than just the surface of the concrete. This method was passed over due to the cost of testing materials. Figure 6 shows a diagram of a penetration test. Maturity testing is defined in ASTM C1074. It uses a specially calibrated meter that measures the temperature of the concrete over time. This measures how much hydration has happened in the concrete. Maturity of the concrete, how much hydration has happened, is assumed to be correlated to the strength of the concrete. Once again, the cost is prohibitive for the test. The final nondestructive test considered was the ultrasonic pulse velocity test. This test uses two transducers to shoot ultrasonic waves to each other. The time is takes for the waves to propagate is used to calculate wave speed. There has been no correlation found between wave speed and concrete hardness due to the number of variables that affect the wave speed. The procedure for this test is found in ASTM C597. The cost and lack of correlation were the main reasons for this test not being used.

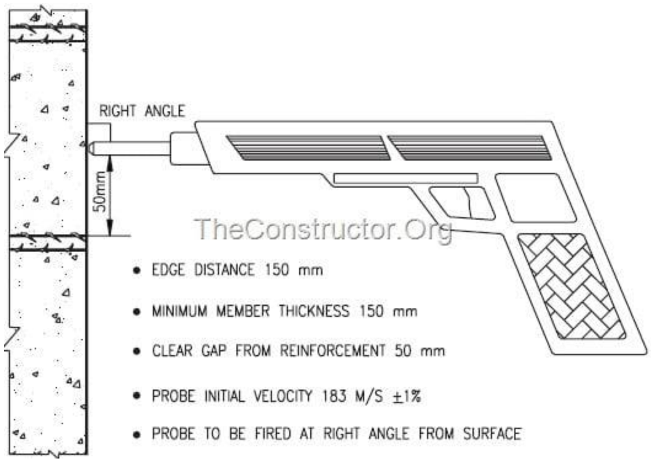


Figure 6 - Diagram of penetration testing equipment

Destructive testing has three main tests, compressive strength, flexure strength, and split tension tests (Michael S Mamlouk). Compressive strength is a very popular test for samples of concrete because of the ease of calculating strength. As it was explained earlier the

Figure 7 - Flexure strength test

lower the w/c ratio the higher the compressive strength. Since w/c ratio is also a driver of concrete quality, the concrete compressive strength is determined to be a good measure of overall cement quality. ASTM C39 is the procedure for compression testing. ASTM C39 states that the geometry of the samples should be a 2:1 height to diameter cylinder. It was decided to use square samples due to availability of reusable sample molds and due to the limiting size of the ovens. A compression testing machine is needed that is calibrated. ISU's civil engineering department already has a calibrated and available machine. This method was chosen to assess the quality of the concrete. The direct value of the total load was recorded, and PSI is a calculated value.

The flexure strength test, ASTM C78, is the most common way to test tensile strength. It is suggested that the samples have a square cross section and a span 3 times the length of the depth of the specimen. Figure 7 shows a flexure strength test on a rectangular sample. The sample is elevated on two bars close to each end and then a load is applied to the center of the sample. This test method was not used as the size of the oven is a prohibiting factor. The split-tension test, ASTM C496, measures the tensile strength of the sample. The cylinder sample has a

Figure 8 - Split tension test

compressive load applied along the diameter of the sample at a constant rate. The failure that develops is due to the tension developed in the transverse direction. Figure 8 shows a cylindrical sample undergoing a split-tension test. Due to the choice of sample geometry previously explained, this test was not utilized.

Thermal Loading

Heat resistance in an elevated temperature environment is a main durability concern for concrete. Concrete has many characteristics that make it ideal for use in NPP including workability, strength, and toughness. It is known that standard concrete loses strength as it is exposed to environments of temperatures 100 ℃ and up (Filmore). It was decided to explore how UHPC would hold up to elevated temperature environments that are like those seen in NPP.

There are several suggestions for limits on how hot the environment the UHPC blend should be exposed to, in order to avoid explosive spalling. A study of UHPC to be used in modular construction chose a temperature limit of 400 ℃ (Jamshaid Sawab). In (Jamshaid Sawab) it is suggested that UHPC gets stronger up to temperatures of 300 ℃ and then strength starts to decrease as temperatures increase. That same research saw explosive spalling at 350 ℃ and 400 ℃ with a UHPC blend without any fibers included. The idea the UHPC loses strength at temperatures above 300 ℃ is suggested in another study (Raizal S.M Rashid). It was decided that the temperature limit in this research would be 300 ℃. This was done because it is assumed that 300 ℃ is a good limit on temperatures that concrete would be exposed to in a SMR, and to attempt to prevent damage to the ovens.

Since concrete is a popular shielding material, the heat generated when radiation is slowed needs to be accounted for as discussed by Kasper William et al. (Kaspar William). This stress can affect the concrete at both the macro- and micro- structural level. The NRC has investigated the phenomena of heat generated by radiation. The results of their study find that the temperature rise in concrete due to neutron radiation is 1.7 ℃. This has no effect on the hydration of concrete. This also is not significant in terms of reaching critical temperature limits of the concrete.

Figure 10 - Spalled UHPC sample from this research

Previous studies have seen samples explosive spall when heating up their UHPC samples. Jamshaid Sawab et al. (Jamshaid Sawab) had UHPC samples explosively spall between 300 ℃ and 350 ℃ for UHPC without fibers and between 350 ℃ and 400 ℃ for UHPC with PVA fibers. Raizal S.M Rashid et al. (Raizal S.M Rashid) had UHPC samples spall at 800 ℃ for silica sand UHPC and at 500 ℃ for magnetite UHPC. Both mixes of concrete had a mixture of PVA and stainless steel fibers. The reason for the explosive spalling is thought to be the evaporation of free water in the concrete. As the water evaporates and expands it needs a place to escape to. In standard concrete the grain structure is loose enough, thanks to the presence of coarse aggregate, for the steam to escape the sample. In UHPC the grain structure is much more dense and the steam can't get out. The building vapor pressure causes an explosive rupture of the piece. The following few figures are examples of UHPC explosively spalling. Figure 9 is the explosive spalling of samples in this research, **f**igure 10 is the explosive spalling experienced in Jamshaid Sawab et al.'s paper (Jamshaid

Figure 9 - Spalled UHPC sample from Jamshaid Sawab's research

Sawab), and figure 11 shows the spalling from Raizal S.M Rashid et al.'s paper (Raizal S.M Rashid).

Figure 11 - Spalled UHPC sample from Raizal S.M. Rashid's work

Irradiation

There are four main types of radiation. Alpha, beta, and neutron radiation are particles, the first two carry a charge, while gamma radiation is energy generally looked at as a photon. Alpha particles are composed of 2 neutron and 2 protons and carry a +2 charge. Beta particles are often described as an electron because they have a similar mass. They can carry either a positive or negative charge. Neutron radiation is just that, a free neutron moving in space. Gamma radiation is similar to x-rays in how they are evaluated. The major difference between x-rays and gamma rays is where the energy originates from, x-rays originate from outside the nucleus whereas gamma rays originate from the nucleus. Each type of radiation has its own unique way of interacting with matter. Concrete is a common shielding material due to its density. The dense structure of concrete is often used to slow particles and gamma rays. Due to the wave like pattern and their lack of charge gamma rays are difficult to stop. It is known that damage can happen from radiation. The potential for damage to the concrete should be tested to ensure that the concrete is viable in NPP.

There are several ways to irradiate a sample, normally insertion into a test or research reactor is arranged. Since this can be a difficult process, it was decided to test how the concrete holds up to gamma irradiation. Idaho National Laboratory, INL, has its Advanced Test Reactor, ATR, facility with a "gamma tube" in the cooling canals for the ATR reactor. The cooling canals provide a space for experiments to cool down after irradiation as well as being essential for refueling the reactor. Figure 12 is a diagram of the gamma tube and illustrates how samples receive their dose. The samples from this research that were sent to INL were contained in an aluminum tube and then lowered into the gamma tube. It is common to have experiments in the tube. Per (Filmore) there is clarification needed with respect to the effect that gamma irradiation has on the mechanical properties of concrete. Since UHPC is a relatively new concrete that is even less known about how irradiation affects the concrete.

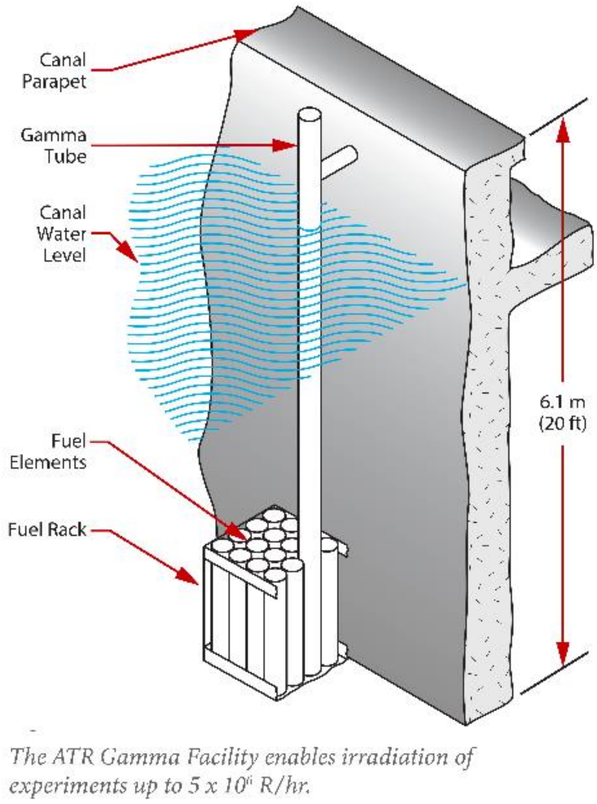


Figure 12 - Diagram of INL's Gamma Tube Facility

There is worry that when the concrete is exposed to radiation that there could be increased heat released from the concrete due to molecular changes in the concrete. In (Kaspar William) it is calculated that at most the temperature rise in concrete from radiation is 1.7 °C. This is from neutrons being captured causing gammas to be emitted from inside the concrete. At this point the temperature rise in concrete is not considered a risk to the overall strength of the concrete.

Chapter 3: Research methodology

Materials Used

The UHPC is from the concrete manufacturer LaFarge. Their UHPC blend is called Ductal JS 1000. Ductal is made from water, super plasticizer (Premia 150), steel fibers, and a proprietary pre-mix (JS 1000 pre-mix) made from cement, silica sand, silica flour, and silica fume. Silica flour is produced from grinding silica sand and can reach sizes as small as 5 μm. The stainless steel fibers are .5” long. Figure 13 shows the stainless steel fibers used in this research. To mix the cement a well-defined ratio of each ingredient is used and mixed following a set procedure (LaFarge). When the concrete was ready it was poured into stainless steel or plastic molds that had a layer of spray lubricant applied. The spray lubricant was used to facilitate in the removal of the cement samples from their molds. Two geometries of samples were initially used for testing; a 2“ square cube and a 2” tall 1.19” diameter cylinder.

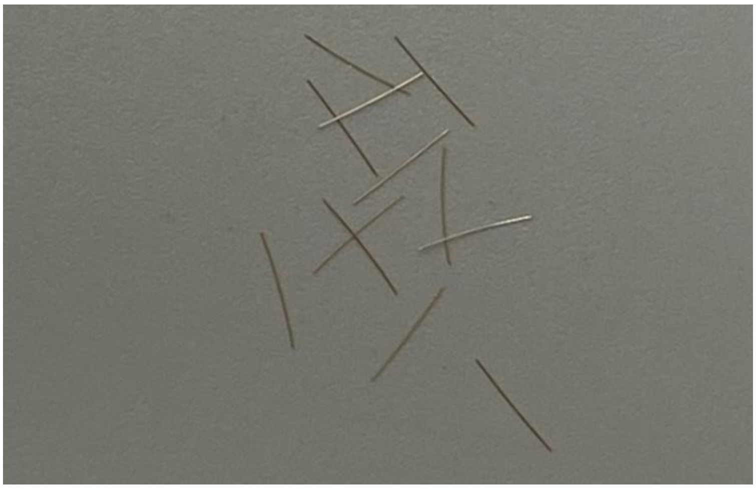


Figure 13 - Stainless steel fibers

The normal concrete is a mixture of cement, fly ash, fine aggregates, coarse aggregates (1/2” pea gravel), and water. Spray lubricant was again used to facilitate the easy removal of samples from their molds. The sample molds were placed on a vibrating table for proper settling of the concrete.

The ovens used were manufactured by Cole-Parmer and were built in Dec 2020 or Jan 2021. They are CBFS518A Single Phase Box Furnaces. The furnaces run on a 120 V power source and can reach a max temperature of 1100 °C. There were four furnaces used for the testing of the samples. Each furnace is controlled by a Cal Controls CAL 9500P Programmable Process Controller. The controllers and their associated thermocouples were installed by the manufacturer. To verify the temperature in the furnace, high temperature probes from Thermoworks were inserted into the furnace. The high temperature probes are a Type K 12" x .06" OD thermocouple. Their model number is THS-113-421-MC. The extra thermocouples are connected to an Omega TC-08 8 Channel Thermocouple USB Data Acquisition Module. The Omega module is connected to a Dell PC with the logging software for the Omega module installed.

The machine used for compression testing is a Gilson MC-300M. It has a 300,000 lb capacity and is run on a 60 V power source.

The scale is an Ohaus Compass CR 2200 it has a 2200g max load. The calipers used are stainless steel and use English units.

Preparations

To verify that the ovens worked and the temperature output on the controller was correct, a series of static temperature tests were performed. The ovens were set to a temperature, starting at 100 ℃ and going up to 1100 ℃ in 50 ℃ increments, and set to hold that temperature for 2 hours. This allowed the ovens to reach equilibrium and for their temperature to be measured against a second thermocouple that was inserted into the oven. On average the ovens ran at a temperature that was 3.9 degrees higher than the reading on controller. This equates to a few percent in total variance; therefore, the results were documented, and no changes were made to the ovens or controllers.

The process to set a program on the controllers is tedious, also there is a learning curve to navigating the controller manually. The purpose of a program is to control the oven temperatures, soak for different amounts of time, and control how fast the oven heats up. There were several different example programs set up to allow for the researchers to get comfortable with the process of setting up a program.

Each individual oven had the researcher manually input a program into the controller. Those programs were used to run experiment 2. It was found that after the program had finished, the ovens stop heating until they were told to do something different. This allowed the samples to return to ambient temperatures without the researcher having to be there to turn off the ovens once the program was done.

An online inventory of samples that had been poured and were ready for testing was set up. The inventory holds the data of pre-testing dimensions and weight, along with post-heat dimensions, weight, and final compressive strength.

Concrete

The procedure for pouring UHPC is very precise on time and ratios. It includes allowing the premix to be mixed in the cement mixer for a time, adding steel fibers and proper mixing time in between steps.

Normal concrete is simple to mix compared to UHPC. When mixing concrete, it is important to note that the main rule is that no more than 1/3 of the total individual ingredient is added at a time. When the concrete is poured into the sample container, the ASTM standard is to rod the concrete or to use vibration to ensure proper settling. Rodding the cement is common way to remove entrapped air and allow the cement to settle. Rodding is jamming a rod, often rebar, into the cement after having been poured. Figure 14 shows UHPC samples after being poured into molds.

Figure 14 - UHPC in sample molds

It was decided to go with a combined cure of 28 days in room temperature water and then a dry air cure for at least one day due to 28 day water bath produces the highest strength in normal concrete (Michael S Mamlouk). The 90-day samples sit in water for only 28 days as well. This is done to get as much strength out of the normal concrete samples as possible. The UHPC samples do not require a combined curing process, but it was decided to match their cure to that of our standard concrete samples for the sake of consistency. Figure 15 shows UHPC cube samples curing in the water bath.

Figure 15 - UHPC samples in water bath

After the samples finished their time in the water bath they were removed and placed to dry for one day. After one day air dry, they were labeled. The side that the label was written on was considered the top of the sample. Measurements of the samples were then taken and labeled according to that orientation. For example, a cube sample had its height, width, and depth measured. The measurement that was labeled the height was a measurement of the side that was labeled to the bottom. This naming convention is critical in determining the compressive strength of the sample in psi as the surface area of the sample needed to be calculated.

Testing

There were multiple sets of tests that were conducted to test the concrete. The two basic tests, Experiments 1 (EXP 1) and 2 (EXP 2), were run with samples that had been allowed to cure for at least 28 days but less than 90 days, or they were allowed to cure for at least 90 days before testing. A third experiment called EXP 1 – INL used samples that were cured for 28 days, with half of the samples being heated at 200 ℃ and the other half not being heated at all, and later sent them to Idaho National Laboratory for exposure in the Gamma Tube of the ATR. All samples were measured and weighed prior to any test campaign.

The first test that was run (EXP 1) was to allow the oven to reach its target temperature and then the sample was inserted into the oven and left in the oven for 6 hours. The 6-hour soak time was chosen after reading Jamshaid Sawab et al. (Jamshaid Sawab). After 6 hours the ovens were turned off and the sample and ovens were allowed to reach ambient temperature before they were measured and weighed. The temperature of the oven was varied each time that the test was run. The temperatures ranged from 100 ℃ to 300 ℃. The temperature was stepped up by 25 ℃ after each run with new samples being tested at the new temperature. The 28-day and 90-day cure sets of EXP 1 were done using two geometries, a 2” square cube and a 2” x 1.19” OD cylinder, and the two types of concrete, UHPC and normal. After doing EXP 1 it was decided to not use the cylinder samples as they were not an ASTM standard size, and the sample molds were not reusable.

After the conclusion of EXP 1, the second experiment (EXP 2) samples were inserted into the oven and then the oven was turned on allowing for the program in the controller to run. The oven would go to a set temperature and soak for a set amount of time before heating up to 250 ℃ and soaking for 6 hours before being turned off and being allowed to slowly cool and reach ambient temperature. The first temperature and soak time were varied with each set; the first temperature had a range of 100 ℃ to 225 ℃ with each variation increasing by 25 ℃. The first soak time started at 1 hr, with subsequent times of 2, 4, 8, and 12 hrs. Each temperature change has the full range of soak times. The allowable ramp rate of the oven was set to 300 ℃/hr. This was done to avoid overtaxing the sample and possibly skewing the results.

This test was done using only the cube samples. Each variation of EXP 2 utilized new samples of both normal concrete and UHPC.

The third test (EXP 1 – INL) utilized both the lab furnaces and gamma irradiation at INL to apply thermal loads to the concrete samples. There are samples that have been heated and not heated in both geometries and types of concrete. The samples that were placed in the oven after it had stabilized at 200 ℃ and were left to soak for 6 hours. In the ATR cooling canals there is a location that has been set aside for experiments to be irradiated called the Gamma Tube Facility. Figure 12 shows a diagram of the Gamma Tube Factility. The samples were placed into aluminum screw top containers, labelled, and then sent to INL for radiation. The samples were placed in the tube with container number 1 being on the bottom and ascending in order. Figure 16 shows samples in the screw top containers. A total of 28 samples were sent, 4 cubes of both types of concrete, 2 having been heated in the oven and two not having been heated prior to irradiation. For the cylinder samples, 10 total of each type of concrete were sent with half being heated prior to irradiation. The samples sat in the Gamma Tube Facility for a total of 61 days. The final exposure received per container is provided in the testing matrix in appendix III. The peak

Figure 16 - Samples in screw top containers

exposure received was 7.59 x 10^7 R. Figure 17 shows the tube that was used to hold the screw top containers while they were in the gamma tube. In (Kaspar William) the listed critical limit of radiation for a concrete bioshield as 1.21 x10^{10} rad, the dose limit is over the lifetime of the reactor. Our samples received a significant acute dose, compared to the lifetime of a reactor. The assumption is that the acute dose, although significantly smaller, will provide a similar stress on the concrete that it would experience over the lifetime of a reactor. Also, per the NRC website, (NRC) the practical conversion of R to rad is 1:1, i.e., 1 R = 1 rad. Since all samples in EXP 1 – INL were irradiated, those samples are then compared to average values of non-irradiated concrete that received similar heat loads.

Figure 17 - Tube used to hold the screw top containers

After the samples finished their time in the oven, they were then tested in a compressive strength machine, see figure 4. Each sample was tested individually, and it was noted which sample side was up to be able to calculate the surface area. The machine has the ability to report sample failure in both total load at failure and instantaneous pressure (in psi) at failure. It was decided to report only the total load at failure to more accurately be able to report instantaneous pressure at failure.

Table 1 shows the baseline strengths of UHPC and normal concrete samples. These are the values that the experiment samples will be tested against.

Baseline Strength

Type	UHPC	Normal Concrete
Strength (psi)	18,500	5,856

Table 1 - Baseline compressive strength values for concrete

Uncertainty Analysis

To calculate the error in the measurements, Stephanie Bell's paper (Bell) was consulted to ensure that error was propagated correctly. There are several areas where error has the potential to skew the results of this research. The primary reported result of the research is the compressive strength of the tested concrete, this is reported in units of psi. The uncertainty from the calipers is systematic uncertainty while the uncertainty from the measurement of the compressive strength of the samples is a random uncertainty. The application of these errors was therefore done different from each other. To obtain psi the surface area of the sample needed to be calculated. The equation for surface area of a cylinder is shown in equation 1.

$$SA = \pi \frac{d^2}{4}$$

Equation 1 - Surface area of a cylinder

- SA = surface area in in^2
- d = diameter of the cylinder in inches.

The surface area of a cube is shown in equation 2.

$$SA = l_1 * l_2$$

Equation 2 - Surface area of a cube

- SA = surface area in in^2
- $l_{1,2}$ = lengths of the cube in inches

The l_1 and l_2 values used to calculate surface area were the height and the width of the samples. This means that the top of the sample was always facing out. To find the uncertainty of the surface area it is required to know the resolution of the calipers. The calipers report values down to .01”. Since the calipers are analog and not digital the resolution was determined to be .005”. Equation 3 was used to calculate the uncertainty of the surface area of a cube sample.

$$\frac{u(A)}{A} = \sqrt{(\frac{u(H)}{H})^2 + (\frac{u(W)}{W})^2}$$

Equation 3 - Uncertainty propagation for surface area of a cubes

- u(i) = uncertainty of the ith variable.
- A = surface area
- H = height of the sample
- W = width of the sample

To calculate the error in surface area of a cylinder sample equation 4 was used.

$$\frac{u(A)}{A} = \pi \frac{\sqrt{(\frac{u(D)}{D})^2}^2}{4}$$

Equation 4 - Uncertainty propagation for surface area of a cylinder

- u(i) = uncertainty of the ith variable
- A = surface area
- D = diameter of the sample

To find the error of the machine the average of the total load of each type of tested sample was taken. Then using equation 5 the standard deviation was found.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}}$$

Equation 5 - Standard deviation calculation

- s = standard deviation
- x_i = the compressive strength of the ith sample
- $\bar{x}$ = the average compressive strength of all the samples of that type
- n = number of samples

It should be noted that the standard deviation of each type of sample means that the standard deviation of a cube of normal concrete was calculated independently of the standard deviation of a UHPC cylinder, and so forth. Now that the uncertainty of the machine and the uncertainty of the surface area are now known the uncertainty of the compressive strength can now be calculated using equation 3 with surface area replaced by compressive strength, and height and width replaced with surface area and total load along with their respective uncertainties. Appendix II shows the values of all samples tested.

Chapter 4: Research findings / results

Experiment 1 (EXP 1)

The UHPC samples increased in strength the higher the temperature went up to the point that the cube samples failed, somewhere between 275 and 300 °C. The cube samples performed better than the cylinders samples with a peak compressive strength at 39,332 ± 872 psi. This was not surprising as previous tests have shown that the 2 in cube samples are stronger than the 2 x 1.19 in cylinders. The cylinders show that the 90-day samples outperformed the 28-day samples, that result was not replicated in the cube samples. The 28-day cube samples tested the highest by a large margin, about 8,000 psi. The results from the samples of normal concrete show a decrease in strength the higher the temperature goes. This was an expected observation as normal concrete begins to degrade at 95 °C (Filmore). These results can be seen in figures 18 and 19. It should be noted that UHPC values are always represented with blue squares and normal concrete values are always represented with red circles.

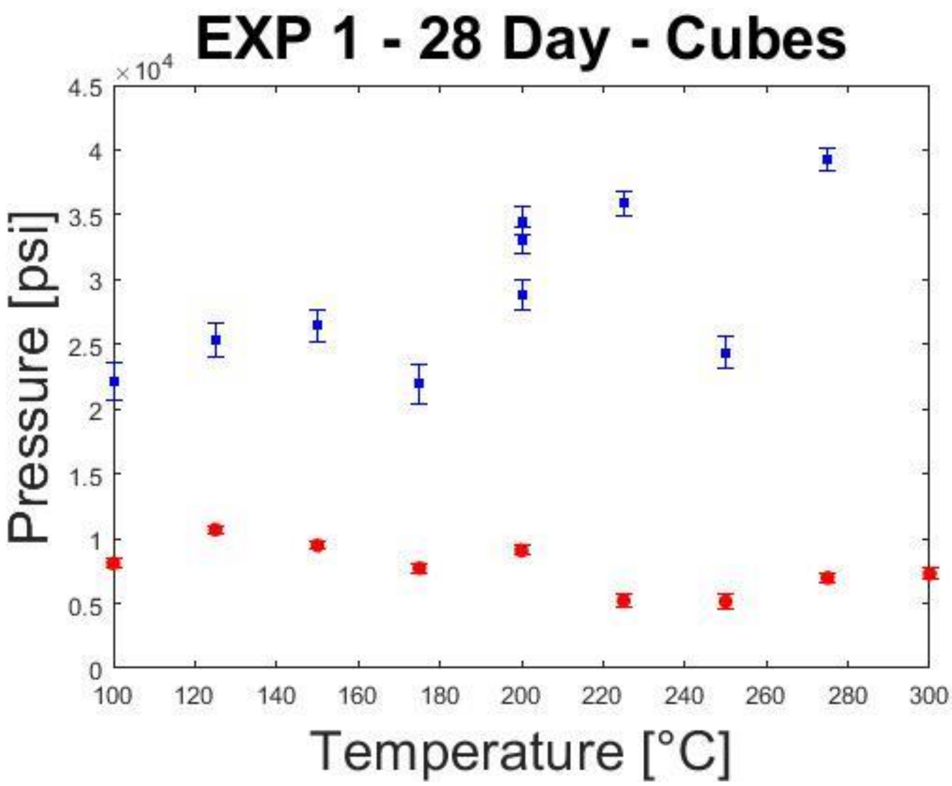


Figure 18 - EXP 1 results for 28-day cured cube samples

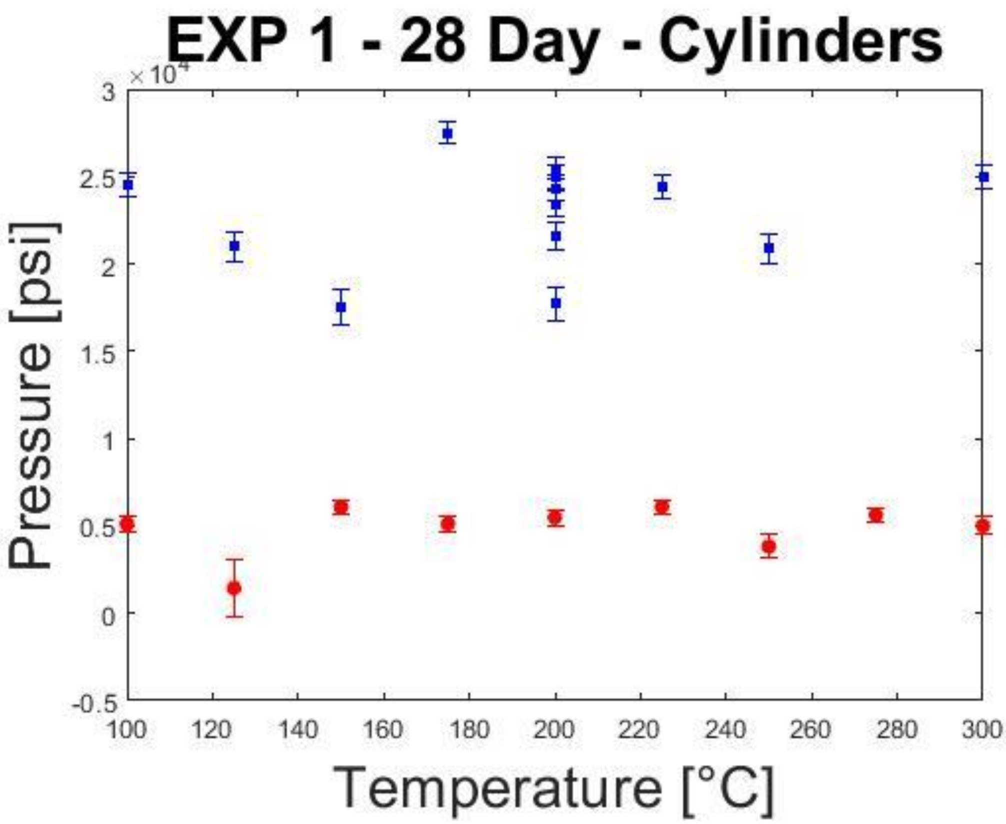


Figure 19 - EXP 1 results for 28-day cured cylinder samples

The UHPC cylinder samples exhibited similar strength values to those of the UHPC cube samples. They had a steady increase in compressive strength as the temperature increased. The surprise is that the normal concrete cylinder samples seemed to increase in strength as the temperature increased in the ovens. The increase in the cylinder samples was much smaller than the overall decrease in the cube samples. This may be an anomaly or due to the abnormally small readings in the first few cylinder tests. The behavior of normal concrete under heat loads is well documented and the results here do follow those findings. These results can be seen in figures 20 and 21.

Previous testing for unheated UHPC resulted in an average compressive strength of 15,080 psi for cube samples and 13,860 psi for the 2 x 1.19 in cylinders. It should be noted that the ASTM standard size for cylinders that produced the best average compressive strength numbers are 3 x 6 in cylinders. Based on previous data even a low-level heat exposure increases the strength of the tested UHPC.

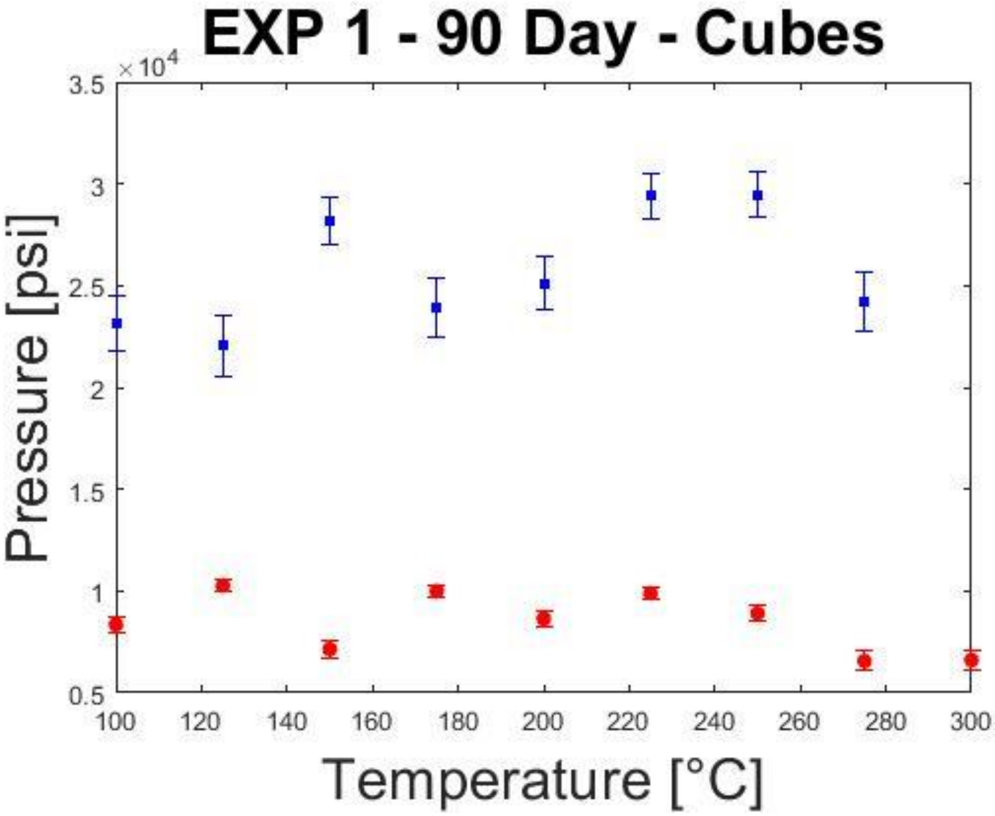


Figure 20 - EXP 1 results for 90-day cured cube samples

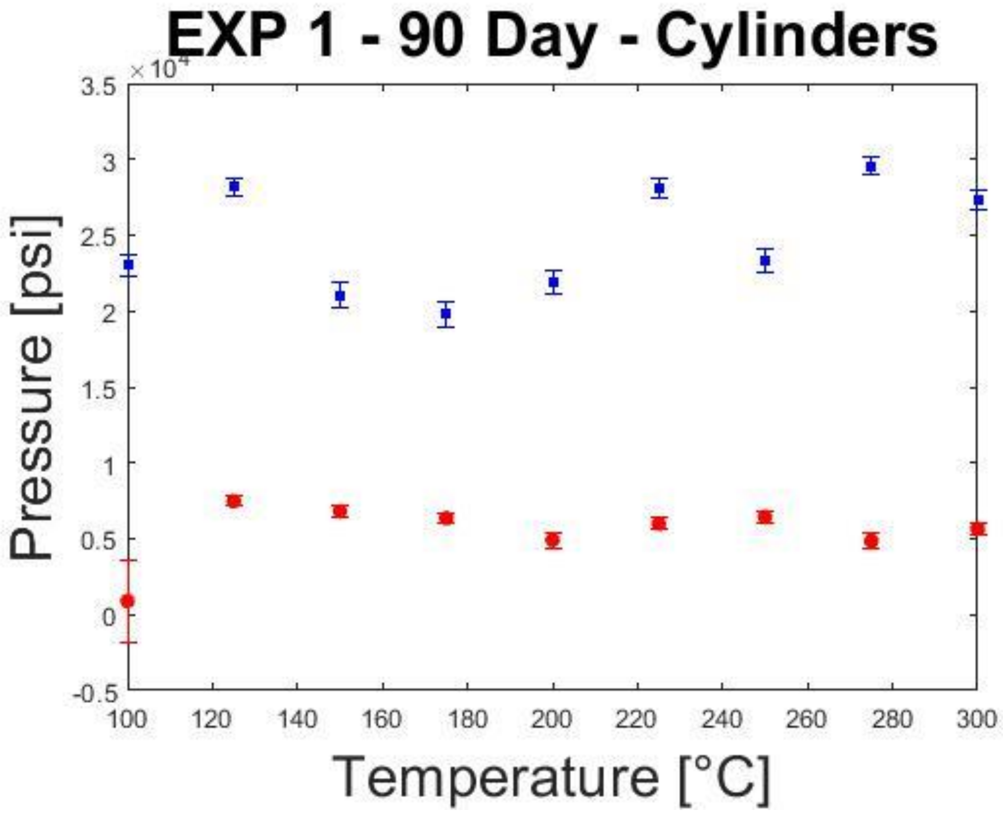


Figure 21- EXP 1 results for 90-day cured cylinder samples

The cylinder samples were very consistent in their fracture types depending on the type of concrete. The normal concrete samples were a type 1 fracture according to ASTM C39, and the UHPC samples were a type 3 fracture. Figure 22 shows the classification of fracture types as defined the ASTM C39. The cube samples were also very consistent in their fracture mode. There is not an ASTM fracture classification for cubes, therefore if the cylinder fracture classification is used, the normal concrete fractured in a type 1 mode and the UHPC fractured in a type 3 mode. Figure 7 illustrates that. It should be noted that even after compression failure the UPHC samples retain their shape and a fraction of their strength as well.

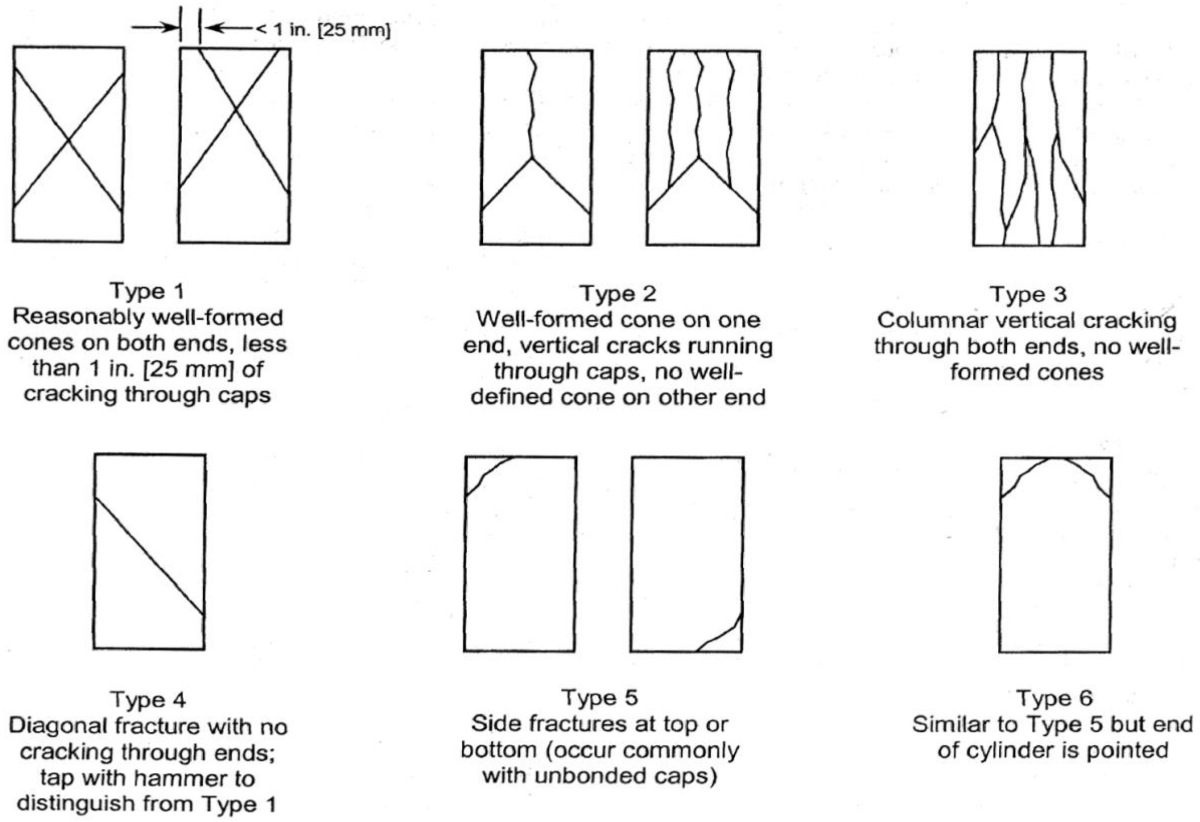


Figure 22 - ASTM fracture types

Experiment 1 (EXP 1) – INL

All the samples in this experiment were irradiated at INL's Gamma Tube Facility. The peak exposure received is 7.59 x 10^7 R. IR indicates that the samples were irradiated, NIR indicates that the samples were not irradiated. The averaged UHPC values for compressive strength were similar whether or not they were heated in an oven. When compared to the average values of heated and unheated UHPC, the irradiated concrete is closer to the strength of unheated UHPC. The cube samples of UHPC had a large variance between comparable tests. The two heated UHPC cubes - U-28-Cu-1 and U-28-Cu-3 - had compressive strength values of 17,398 ± 1,934 psi and 25,863 ± 1,366 psi, respectively. The unheated samples - U-28-Cu-5 and U-28-Cu-7 - had a similar disparity in compressive strength, with values of 16,242 ± 2,219 psi and 24,665 ± 2,297 psi, respectively. The heated samples show a decrease of 39 % in compressive strength for the UHPC cubes and a decrease of 19 % for the cylinder samples.

Figures 23 and 24 show the averaged compressive strength of the heated and unheated samples that were irradiated compared with the unirradiated compressive strengths of both types of concrete. The unheated samples show an increase of average compressive strength. The cylinder UHPC samples demonstrated an increase in the average compressive strength by 3 % and in the cubes by 49 %.

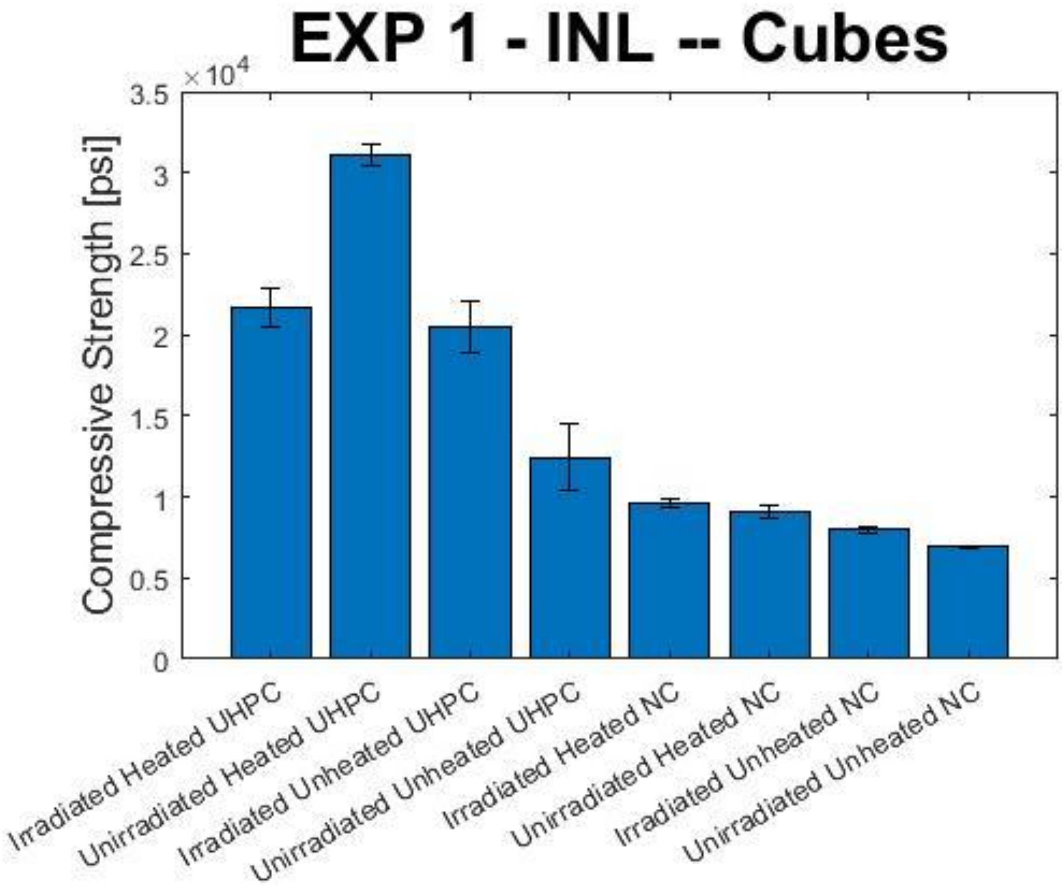


Figure 23 - EXP 1 - INL results for cube samples

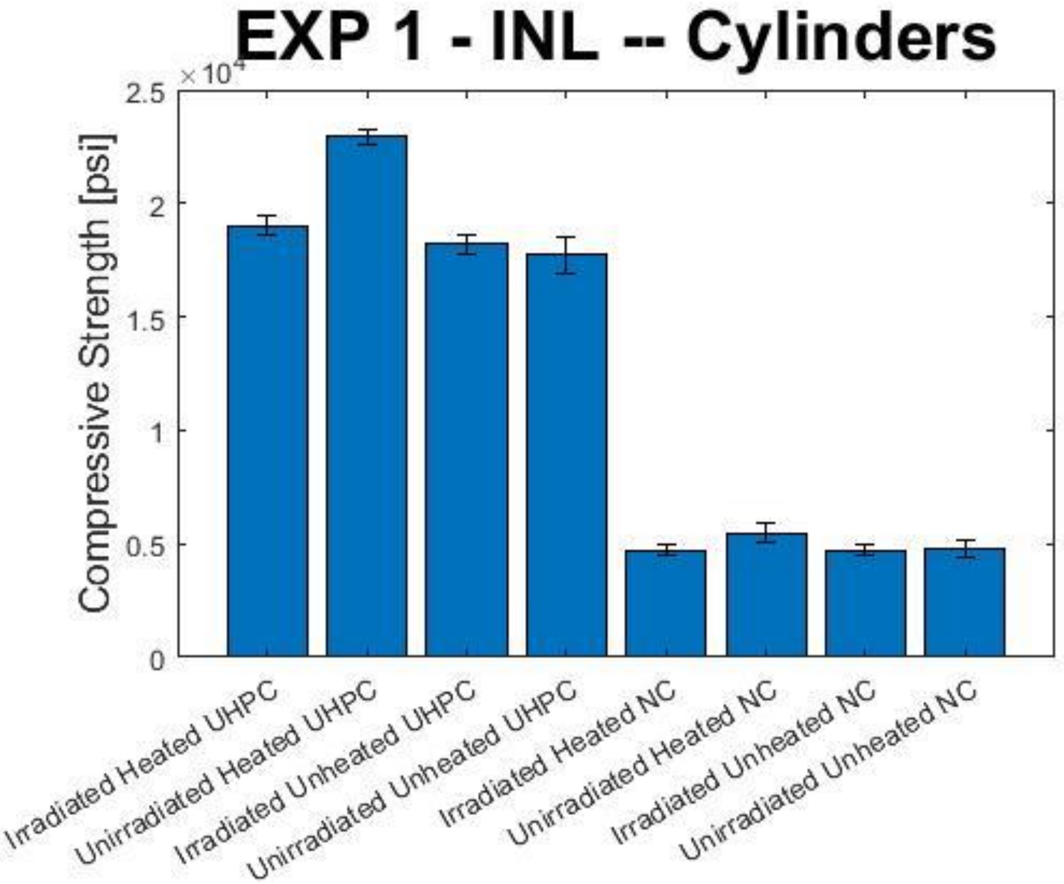


Figure 24 - EXP 1 - INL results for cylinder samples

The normal concrete samples held more consistent results from sample to sample than the UHPC samples. The heated samples saw a decrease in strength for the cylinders and an increase in strength for the cube samples. The heated cylinders saw their strength decrease by 15 % and the cube increased by 6 %. The samples that were not exposed to heat prior to irradiation saw an increase in compressive strength after they were irradiated. The cylinders saw less than 1 % increase and the cubes had an overall increase in average compressive strength of 14 %.

Experiment (EXP) 2

As was seen in EXP 1, in general the compressive strength of the UHPC samples increases as the temperature increases. This happens regardless of time in the oven. The maximum compressive strength reached in EXP 2 is 34,951 ± 926 psi, by sample U-90-Cu-37. The normal concrete samples kept a stable compressive strength independent of time in the oven. The average compressive strength of the normal concrete samples is 6966 ± 66 psi. The results of EXP 2 with temperature along the abscissa for both the 28 day and 90 samples can be found in Appendix V.

The results of compressive strength compared to time in the oven are shown in appendix V. The strength of the 28-day UHPC samples decreased as they spend time in the oven. The 90-day UHPC samples maintained their strength across the different soak times. The normal concrete samples of both cure times exhibit a decrease in compressive strength.

Figures 25 - 28 show the averaged values for EXP 2 at each initial temperature or at the time spend at the initial temperature with the initial temperature along the abscissa first with the time at the initial temperature along the abscissa second. As can be seen from the following graphs as the temperature increased the average values of the compressive strength of the UHPC samples increases while the normal concrete samples remain stable in their compressive strength. When compared to the time in the oven the UHPC samples show a decrease in strength with the normal concrete samples again remaining stable.

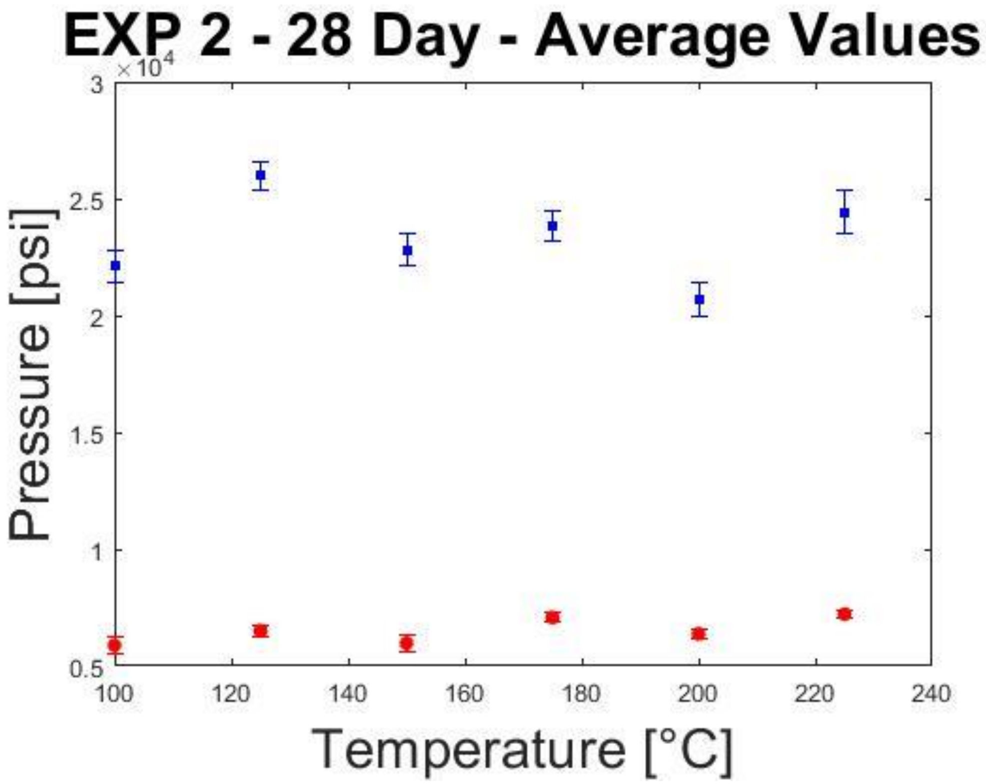


Figure 25 - EXP 2 time averaged results for 28 day cured samples

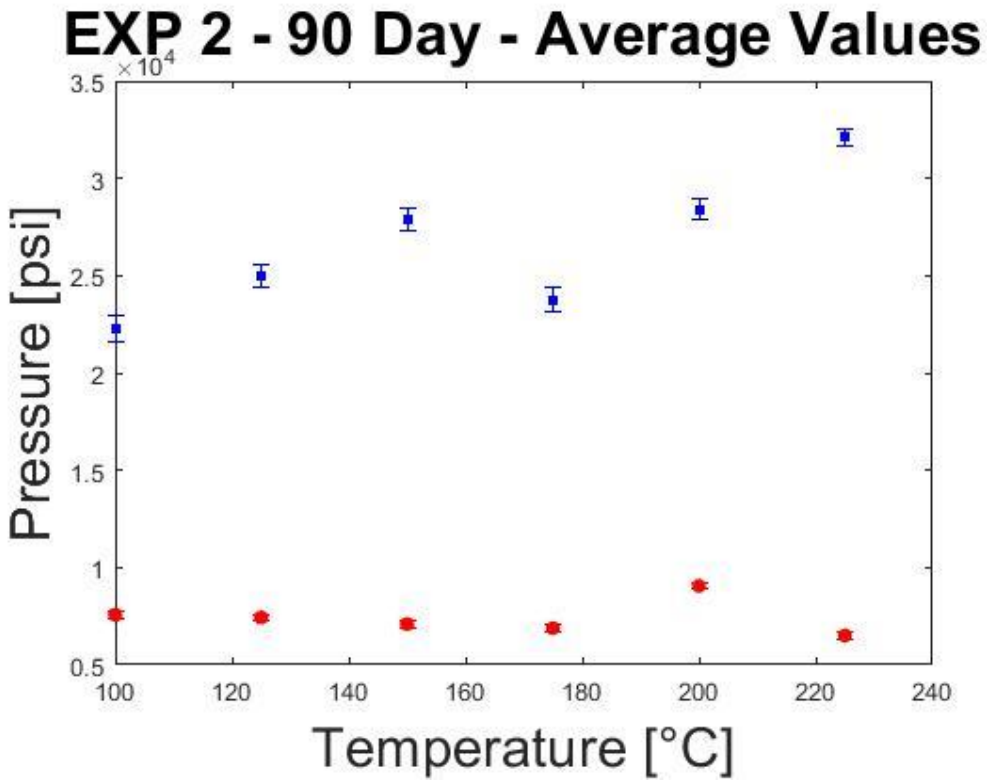


Figure 26 - EXP 2 time averaged results for 90-day cured samples

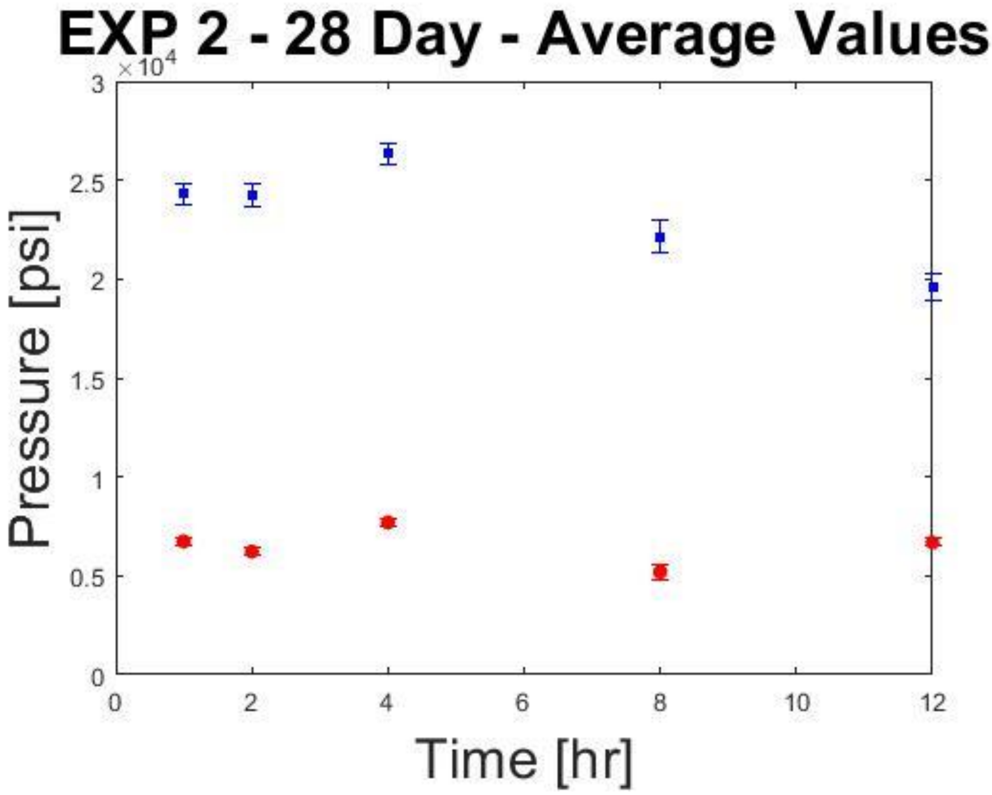


Figure 27 - EXP 2 temperature averaged results for 28-day cured samples

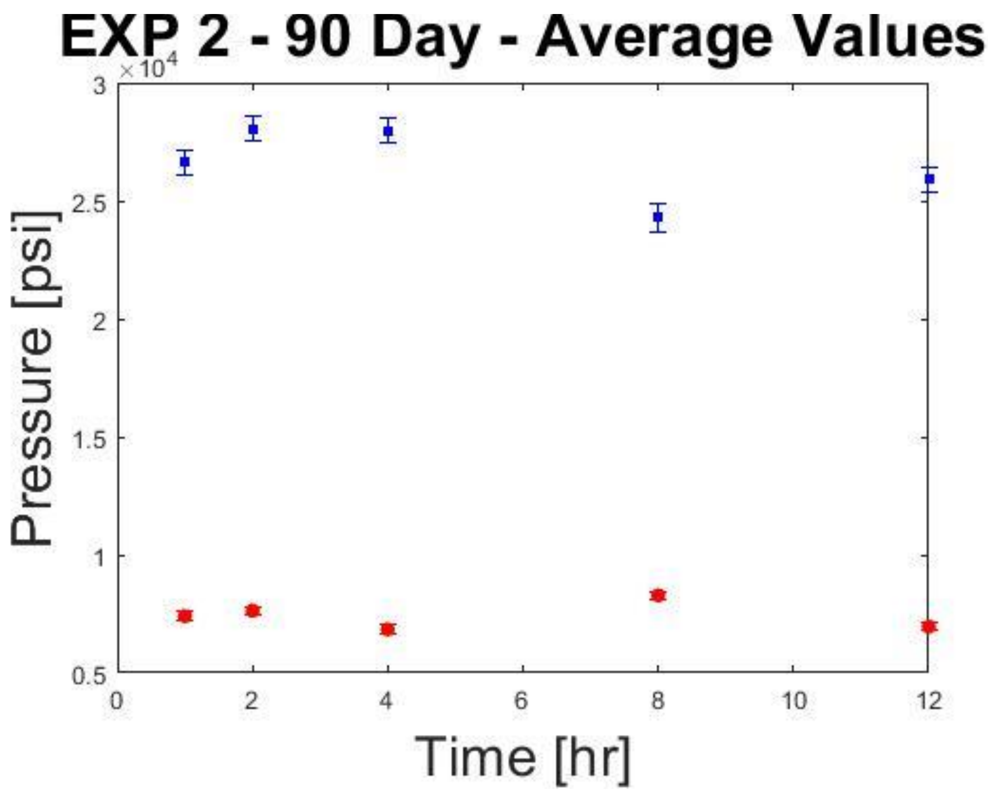


Figure 28 - EXP 2 temperature averaged results for 90-day cured samples

Chapter 5: Discussion and Analysis of Findings

EXP 1

The UHPC samples increased in strength as a function of increasing temperature up to the point that the samples failed, somewhere between 275 and 300 ℃. The cube samples performed better than the cylinders samples in their compressive strength. This is not surprising as previous tests have shown that the 2 in cube samples are stronger than the 2 x 1.19 in cylinders. The cylinders show that the 90-day samples outperformed the 28-day samples, that result was not replicated in the cube samples. The largest value of the 28-day cube samples produced the highest compressive strength. That value is about 5,000 psi higher than any other value from EXP 1. A reason for an increase in strength in UHPC is due to pozzolanic reactivity of the materials allowing the concrete to produce longer C-S-H chains (Jamshaid Sawab)**.** Longer C-S-H chains provide more strength. Previous testing for unheated UHPC resulted in an average compressive strength of 15,080 psi for cube samples and 13,860 psi for the 2 x 1.19 in cylinders. It should be noted that the ASTM standard size for cylinders that produced the best average compressive strength numbers is 3 x 6 in cylinders. Based on data from Jamshaid Sawab et al. (Jamshaid Sawab) even a low-level heat exposure increases the strength of the tested UHPC. This bodes well for the use of UHPC in nuclear applications as the expected heat exposure for containment structures is up to 200 ℃ with radiation exposure potentially pushing the temperature up to 250 ℃ (F. Vodak). This keeps the temperatures below the spalling zone for the UHPC that we tested.

The results from the cube samples of normal concrete show a decrease in strength the higher the temperature goes. This is expected based on results such as those discussed in D.L. Filmore's paper (Filmore). The surprise is that the cylinder samples seemed to increase in strength as the temperature increased in the ovens. The increase in the cylinder samples is much smaller than the overall decrease in the cube samples. This may be an anomaly or that we had abnormally small readings in the first few cylinder tests. The behavior of normal concrete under heat loads is well documented, and the results here do follow those findings.

Figure 29 - Cylindrical samples after compression testing

The cylinder samples were very consistent in their fracture types depending on the type of concrete. The normal concrete samples were a type 1 fracture and the UHPC samples were a type 3 fracture. Figure 29 shows a sample of both normal concrete and UHPC after compression testing. The cube samples were also very consistent in their fracture mode. There is not an ASTM fracture classification for cubes. If we use the cylinder fracture classification the normal concrete fractured in a type 1 mode and the UHPC fractured in a type 3 mode. Figure 51 illustrates the type 1 fracture of the normal concrete cylinder samples. It should be noted that even after compression failure, the UPHC samples retain their shape and a fraction of their strength as well.

The explosive spalling of the samples at temperatures between 275 and 300 is of concern. Figure 30 shows a UHPC sample after explosive spalling. Since the spalling happened for both 28 and 90 day samples, simply letting the samples age before exposure to high levels of heat is not a fool proof way to prevent explosive spalling. Other work to prevent explosive spalling (Jamshaid Sawab). Future work could be done to explore the possibility of thermal cycling as a method to remove the free water in the samples.

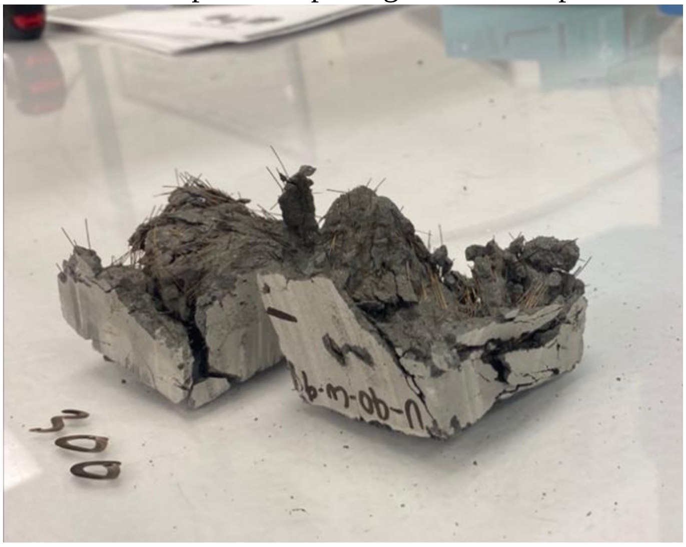


Figure 30 - An explosively spalled UHPC sample

EXP 1 – INL

The decrease in strength from irradiation shown in the UHPC cube samples is troubling. The change in the heated UHPC cubes is a 39 % decrease in strength, and the heated cylinder samples show a decrease of 19%. This could be due to the silica in the C-S-H breaking down and leading to a decrease in strength (Kaspar William). The unheated UHPC samples show an increase in strength. At this time, it is not known why the samples' compressive strength increased when they were not exposed to a thermal load prior to irradiation. This result is unexpected and therefore more research into this phenomenon is suggested.

Unsurprisingly, the normal concrete did not change much. There was some variance on what samples increased in strength and what samples decreased in strength. Overall, the concrete samples stayed about the same with respect to the compressive strength.

Even with the decrease in strength in the heated UHPC samples and with the relative stability of the normal concrete samples, UHPC is still significantly stronger. The decrease in strength for the heated doesn't lower the overall strength below the baseline value of UHPC. The robustness of UHPC is evident in the overall strength being higher than its baseline value.

EXP 2

As discussed previously only 2" cube samples were used for this test. Since both the initial temperature and the first soak time were variables that were changed there are two different ways to look at the data. The main test of concrete quality remains the compressive strength. First the initial temperature was used as the values along the abscissa with psi accounting for the values along the ordinate. The overall strength in the UHPC 28-day samples increased as the temperature increased. These results are consistent with the findings in EXP 1 and those found by Gai-Fei Peng et al. (Gai-Fei Peng), Jamsaid Sawab et al. (Jamshaid Sawab), and Raizal S.M. Rashid (Raizal S.M Rashid). . When the strength of the samples is compared to the time that the samples spent in the oven the strength of the samples decreases as they spend more time in the oven. These results are consistent with the results found by D.L Filmore (Filmore). The compressive strength of 90-day UHPC samples follow the same pattern of increasing with temperature and decreasing with time in the oven. Table **2** shows the averaged values of 28- and 90-day UHPC samples compared to the baseline unheated strength. When the average values of the 28-day and 90-day UHPC samples are compared to the calculated baseline values the overall strength of the UHPC is still stronger than its baseline unheated value. This suggests that the UHPC is robust and holds up well to aging.

The normal concrete samples follow a similar pattern as EXP 1. The overall strength of the samples doesn't change much with the increase of temperature. When compared with time in the oven, the strength of normal concrete samples does not change by any significant amount. Table 2 shows the averaged values of the 28- and 90-day samples of both types of concrete compared to the baseline value.

Type	Baseline	Cure	
		28 Day	90 Day
Normal	5,856	6,530	7,424
UHPC	18,000	23,315	26,573

Table 2 - Averaged EXP 2 values with baseline concrete strength

The weight change in samples differ according to the type of concrete. Normal concrete loses on average 5% of its weight after time in the oven. The UHPC only loses 1.5% of its weight after time in the oven; this is due to the lower w/c ratio in UHPC. As discussed above, a lower w/c ratio results in less free water in the sample, which allows the UHPC to use more of its water in the hydration process and lowers the number of voids in the concrete. Hydration is the process that creates C-S-H chains which increase the resistance to fracture. Fracture methods for the concrete samples in EXP 2 are the same as in EXP 1.

Chapter 6: Conclusion and recommendations

The goal of this research was to determine the resilience of UHPC in a variety of scenarios relevant to use in a NPP. A campaign of separate effects tests, namely, to determine the performance of UHPC under a series of thermal stressing and gamma irradiation experiments, were executed. The motivation of this work was to explore the possibility of using UHPC in future NPP. It was found that the UHPC blend, Ductal UHPC mix by Lafarge, increases in strength as the temperature that it is exposed to increases. However, when the temperature gets close to 300 ℃, there is a risk of samples explosively spalling (Jamshaid Sawab) (Raizal S.M Rashid). The UHPC loses strength when irradiated after it was heated in a box oven, but it gains strength when irradiated without being heated in a box oven. Even with the decrease in strength after irradiation and thermal loading the strength of the UHPC is above its baseline values, which provides added safety for concrete structures. Finally, we saw that the UHPC is resistant to aging. Although samples decreased in strength from longer times in the ovens their overall strength is higher than baseline values.

The findings summarized above bode well for nuclear applications. The concrete shielding and containment structures are not expected to receive thermal loads larger than 250 ℃ (Jamshaid Sawab) (Filmore). This temperature allows for a significant factor of safety to an already robust concrete mixture. Initial strength of UHPC is about 4 times that of normal concrete and when it is heated the increasing strength is a bonus. Even after more robust testing in EXP 2 and EXP 1 – INL, the strength of UHPC is significantly stronger than normal concrete.

It should be noted that the values for the cube samples used in EXP 1 – INL have a large variance, largely due to low number of samples sent for each type of concrete: 2 having been heated in the box oven, and 2 not having been heated. Another contributor to the uncertainty of the results was the lack of multiple samples tested at each temperature and time for EXP 1 and EXP 2. In other words, one sample can skew the overall results. More samples will allow a clearer view on the effects of the tests on the samples. If UHPC is to be allowed to be used in NPP in the US, it must fulfill the guidelines set out in ANSI/ANS 6.4.2 which includes how do the samples hold up to neutron irradiation.

Moving forward research into UHPC should include integral effects tests, which would include exposing the samples to heat and radiation at the same time. Also, it is suggested that heated and irradiated samples be tested in tension as well as compression. Further exploration into ways to prevent explosive spalling is another area that deserves more research. The ultimate goal of this research is to help UHPC be qualified for use in NPP. How the concrete resists aging due to thermal loads, as well as sources of radiation, are only part of the characterization needed to fulfill the guidelines in ANSI/ANS 6.4.2. It is suggested that all further work focus on those guidelines with the purpose of having UHPC qualified for use by the NRC.

Works Cited

American Nuclear Society. *Specification for Radiation Materials*. La Grange Park: ANS, 2006.

Basu Prabier C, Labbe Pierre, Naus Dan J. "NUCLEAR POWER PLANT CONCRETE STRUCTURES." *Structural Mechanics in Reactor Technology*. San Francisco, 2013.

Bell, Stephanie. *A Beginner's Guide to Uncertainty Measurement*. Teddington: National Phyiscal Laboratory, 2001.

F. Vodak, R. Cerny, J. Drchalova, S. Hoskova, O. Kapickova, O Michalko, P. Semerak, J Toman. "Thermophysical Properties of Concrete for Nuclear-Safety Related Structures." *Cement and Concrete Research* 27.3 (1997): 415 - 426.

Fei Ren, John Jy-An Wang, and Beverly P. DiPaolo. "Thermal Expansion Study and Microstructural Characterization of High-Performance Concretes." *Journal of Materials in Civil Engineering* 25.10 (2013): 1574-1578.

Filmore, D. L. *Literature Review of the Effects of Radiation and Temperature on the Aging of Concrete*. Idaho Falls: INEEL, 2004.

Gai-Fei Peng, Xu-Jing Niu, Ya-Jie Shang, Deng-Ping Zhang, Xi-Wang Cheng, Hong Ding. "Combined Curing as a Novel Approach to Improve Resistance of Ultra-High-Performance Concrete to Explosive Spalling Under High Temperature and its Mechanical Properties." *Cement and Concrete Research* 109 (2018): 147-158.

Jamshaid Sawab, Ing Lim, Y.L. Mo, Mo Li, Hong Wang, Maria Guimaraes. *Ultra-High-Performance Concrete and Advanced Manufacturing Methods for Modular Construction*. Houston: University of Houston, 2016.

Kaspar William, Yunping Xi, Dan Naus, Herman L. Graves. *A Review of the Effects of Radiation on Microstructure and Properties of Concretes Used in Nuclear Power Plants*. Washington DC: Nuclear Regulatory Commision, 2013.

LaFarge. "Ductal Jointing Procedure." February 2014.

Michael S Mamlouk, John P Zaniewski. *Materials for Civil and Construction Engineers*. Upper Saddle River: Prentice Hall, 2011.

Muhammad Umar Khan, Shamsad Ahmad, Akhtar Abbas Naqvi, Husain Jubran Al-Gahtani. "Shielding Performance of Heavy-Weight Ultra-High-Performance Concrete Against Nuclear Radiation." *Progress in Nuclear Energy* 130 (2020).

N.M. Azreen, Raizal S.M. Rashid, M Haniza, Y.L. Voo, Y.H. Mugahed Amran. "Radiation Sheilding of Ultra-High-Performance Concrete." *Construction and Building Materials* 172 (2018): 370-377.

NRC. *Radiation and its Health Effects: Measuring Radiation*. 1 September 2022. <https://www.nrc.gov/about-nrc/radiation/health-effects/measuring-radiation.html>.

Raizal S.M Rashid, S. Mohammed Salem, N.M. Azreen, Y.L. Voo, M. Haniza, A.A. Shukri, Mohd-Syukri Yahya. "Effect of Elevated Temperature to Radiation Shielding of Ultra-High-Performance Concrete with Silica Sand or Magnetite." *Contruction and Building Materials* 262 (2020).

UHPC Solutions North America. *Bridge Rehab Case Studies*. n.d. UHPC Solutions North America. 19 Sept 2022. <https://www.uhpcsolutions.com/case-studies>.

Appendices

Appendix I – Testing Matrices

EXP 1 - 28 Day Cure				
Test Set	Temperature (Deg C)	Time (hr)	Serial Numbers	Oven
1	100	6	U-28-Cy-21	1
			U-28-Cu-9	2
			N-28-Cy-1	3
			N-28-Cu-1	4
2	125	6	U-28-Cy-22	3
			U-28-Cu-10	4
			N-28-Cy-2	3
			N-28-Cu-2	4
3	150	6	U-28-Cy-23	1
			U-28-Cu-11	2
			N-28-Cy-3	3
			N-28-Cu-3	2
4	175	6	U-28-Cy-24	3
			U-28-Cu-12	4
			N-28-Cy-4	1
			N-28-Cu-4	2
5	200	6	U-28-Cy-25	1
			U-28-Cu-13	2
			N-28-Cy-5	3
			N-28-Cu-5	4
6	225	6	U-28-Cy-26	3
			U-28-Cu-14	4
			N-28-Cy-6	3
			N-28-Cu-31	1
7	250	6	U-28-Cy-27	1
			U-28-Cu-15	2
			N-28-Cy-7	4
			N-28-Cu-32	2
8	275	6	U-28-Cy-28	3
			U-28-Cu-16	4
			N-28-Cy-8	1
			N-28-Cu-33	3
9	300	6	U-28-Cy-29	1

			U-28-Cu-17	2
			N-28-Cy-9	3
			N-28-Cu-30	4

EXP 1 - 90 Day Cure				
Test Set	Temperature (Deg C)	Time (hr)	Serial Numbers	Oven
1	100	6	U-90-Cy-1	1
			N-90-Cy-1	1
			N-90-Cu-1	2
			U-90-Cu-1	1
2	125	6	U-90-Cy-2	2
			N-90-Cy-2	3
			N-90-Cu-2	4
			U-90-Cu-2	2
3	150	6	U-90-Cy-3	3
			N-90-Cy-3	1
			N-90-Cu-3	2
			U-90-Cu-3	3
4	175	6	U-90-Cy-4	4
			N-90-Cy-4	3
			N-90-Cu-4	4
			U-90-Cu-4	4
5	200	6	U-90-Cy-5	1
			N-90-Cy-5	1
			N-90-Cu-5	2
			U-90-Cu-5	1
6	225	6	U-90-Cy-6	2
			N-90-Cy-6	3
			N-90-Cu-6	4
			U-90-Cu-6	2
7	250	6	U-90-Cy-7	3
			N-90-Cy-7	1
			N-90-Cu-7	2
			U-90-Cu-7	3
8	275	6	U-90-Cy-8	4
			N-90-Cy-8	3
			N-90-Cu-8	4
			U-90-Cu-8	4
9	300	6	U-90-Cy-9	1
			N-90-Cy-9	1

			N-90-Cu-9	2
			U-90-Cu-9	1

EXP 1 - INL				
Test Set	Temperature (Deg C)	Time (hr)	Serial Numbers	Oven
1	200	6	U-28-Cy-1	1
			U-28-Cy-2	2
			U-28-Cy-3	3
			U-28-Cy-4	4
2	200	6	U-28-Cy-5	1
			U-28-Cy-6	2
			U-28-Cy-7	3
			U-28-Cy-8	4
3	200	6	U-28-Cy-9	1
			U-28-Cy-10	2
			U-28-Cu-1	3
			U-28-Cu-2	4
4	200	6	U-28-Cu-3	1
			U-28-Cu-4	2
5	200	6	N-28-Cu-7	3
			N-28-Cu-9	4
6	200	6	N-28-Cy-10	3
			N-28-Cy-11	4
			N-28-Cy-12	1
7	200	6	N-28-Cy-13	3
			N-28-Cy-14	4

28 Day Cure						
Test Set	Temperature (Deg C)		Time (hr)		Serial Numbers	Oven
	1	2	1	2		
1	100	250	1	6	U-28-Cu-47	1
					N-28-Cu-10	1
			2		U-28-Cu-22	1
					N-28-Cu-14	1
			4		U-28-Cu-26	1
					N-28-Cu-18	1
			8		U-28-Cu-30	1
					N-28-Cu-22	1
			12		U-28-Cu-34	1
					N-28-Cu-26	1
2	125	250	1	6	U-28-Cu-19	2

					N-28-Cu-11	2
			2		U-28-Cu-23	2
					N-28-Cu-15	2
			4		U-28-Cu-27	2
					N-28-Cu-19	2
			8		U-28-Cu-31	2
					N-28-Cu-23	2
			12		U-28-Cu-35	2
					N-28-Cu-27	2
3	150	250	1	6	U-28-Cu-20	3
					N-28-Cu-12	3
			2		U-28-Cu-24	3
					N-28-Cu-16	3
			4		U-28-Cu-28	3
					N-28-Cu-20	3
			8		U-28-Cu-32	3
					N-28-Cu-24	3
			12		U-28-Cu-36	3
					N-28-Cu-28	3
4	175	250	1	6	U-28-Cu-21	4
					N-28-Cu-13	4
			2		U-28-Cu-25	4
					N-28-Cu-17	4
			4		U-28-Cu-29	4
					N-28-Cu-21	4
			8		U-28-Cu-33	4
					N-28-Cu-25	4
			12		U-28-Cu-37	4
					N-28-Cu-29	4
5	200	250	1	6	U-28-Cu-18	1
					N-28-Cu-34	1
			2		U-28-Cu-38	1
					N-28-Cu-35	2
			4		U-28-Cu-39	2
					N-28-Cu-38	1
			8		U-28-Cu-42	1
					N-28-Cu-39	2
			12		U-28-Cu-43	2
					N-28-Cu-42	2
6	225	250	1	6	U-28-Cu-40	3
					N-28-Cu-36	3

			2		U-28-Cu-41	4
					N-28-Cu-37	4
			4		U-28-Cu-44	3
					N-28-Cu-40	3
			8		U-28-Cu-45	4
					N-28-Cu-41	4
			12		U-28-Cu-46	4
					N-28-Cu-43	4

90 Day Cure						
Test Set	Temperature (Deg C)		Time (hr)		Serial Numbers	Oven
	1	2	1	2		
1	100	250	1	6	U-90-Cu-10	1
					N-90-Cu-10	1
			2		U-90-Cu-14	1
					N-90-Cu-14	1
			4		U-90-Cu-18	1
					N-90-Cu-18	1
			8		U-90-Cu-22	1
					N-90-Cu-22	1
			12		U-90-Cu-26	1
					N-90-Cu-26	1
2	125	250	1	6	U-90-Cu-11	2
					N-90-Cu-11	2
			2		U-90-Cu-15	2
					N-90-Cu-15	2
			4		U-90-Cu-19	2
					N-90-Cu-19	2
			8		U-90-Cu-23	2
					N-90-Cu-23	2
			12		U-90-Cu-27	2
					N-90-Cu-27	2
3	150	250	1	6	U-90-Cu-12	3
					N-90-Cu-12	3
			2		U-90-Cu-16	3
					N-90-Cu-16	3
			4		U-90-Cu-20	3
					N-90-Cu-20	3
			8		U-90-Cu-24	3
					N-90-Cu-24	3

			12		U-90-Cu-28	3
					N-90-Cu-28	3
4	175	250	1	6	U-90-Cu-13	4
					N-90-Cu-13	4
			2		U-90-Cu-17	4
					N-90-Cu-17	4
			4		U-90-Cu-21	4
					N-90-Cu-21	4
			8		U-90-Cu-25	4
					N-90-Cu-25	4
			12		U-90-Cu-29	4
					N-90-Cu-29	4
5	200	250	1	6	U-90-Cu-30	1
					N-90-Cu-30	1
			2		U-90-Cu-31	2
					N-90-Cu-31	2
			4		U-90-Cu-32	1
					N-90-Cu-32	1
			8		U-90-Cu-33	2
					N-90-Cu-33	2
			12		U-90-Cu-34	1
					N-90-Cu-34	1
6	225	250	1	6	U-90-Cu-35	3
					N-90-Cu-35	3
			2		U-90-Cu-36	4
					N-90-Cu-36	4
			4		U-90-Cu-37	3
					N-90-Cu-37	3
			8		U-90-Cu-38	4
					N-90-Cu-38	4
			12		U-90-Cu-39	3
					N-90-Cu-39	4

Appendix II – Sample Inventory

EXP 1										
Label	Post Heat				Experiment #	Temperature	Surface Area (in^2)	Loading at Failure		Error
	Weight	Height	Width	Depth				Pounds	PSI	
U-28-Cu-2	335	1.98	2.01	2.04	1	200	3.98	137,330	34,507	1,066
U-28-Cu-4	353	2.09	2.03	2.03	1	200	4.24	122,130	28,786	1,124
U-28-Cu-9	340	2.13	2.01	2.02	1	100	4.28	94,910	22,169	1,433
U-28-Cu-10	362	2.13	2.01	2.06	1	125	4.28	108,400	25,319	1,255
U-28-Cu-11	346	2.09	2.02	2.03	1	150	4.22	111,650	26,446	1,236
U-28-Cu-12	334	2.07	2.01	2.01	1	175	4.16	91,420	21,972	1,531
U-28-Cu-13	332	2.04	2.02	2.00	1	200	4.12	136,050	33,015	1,039
U-28-Cu-14	344	2.01	2.02	2.04	1	225	4.06	145,700	35,885	985
U-28-Cu-15	352	2.17	2.02	1.99	1	250	4.38	106,770	24,358	1,245
U-28-Cu-16	341	2.05	2.01	2.01	1	275	4.12	162,070	39,333	872
U-28-Cu-17	Explosive Spalling				1	300	-	-	-	
U-90-Cu-1	356	2.12	2.03	2.06	1	100	4.30	99,760	23,181	1,357
U-90-Cu-2	336	2.07	2.01	2.00	1	125	4.16	91,670	22,032	1,527

U-90-Cu-3	338	2.01	2.10	1.99	1	150	4.22	118,830	28,152	1,161
U-90-Cu-4	342	2.02	2.02	2.07	1	175	4.08	97,560	23,909	1,463
U-90-Cu-5	342	2.04	2.04	2.05	1	200	4.16	104,530	25,118	1,339
U-90-Cu-6	347	2.05	2.07	2.02	1	225	4.24	124,830	29,417	1,100
U-90-Cu-7	335	2.07	2.03	2.05	1	250	4.20	123,840	29,471	1,119
U-90-Cu-8	326	2.01	2.01	2.08	1	275	4.04	97,860	24,222	1,473
U-90-Cu-9	Spalling				1	300	-	-	-	
N-28-Cu-1	299	2.03	2.02	2.00	1	100	4.10	33,160	8,087	371
N-28-Cu-2	297	2.00	2.01	2.03	1	125	4.02	43,000	10,697	292
N-28-Cu-3	295	2.02	2.00	2.00	1	150	4.04	38,280	9,475	326
N-28-Cu-4	288	2.00	2.00	2.03	1	175	4.00	30,880	7,720	408
N-28-Cu-5	273	1.98	2.01	2.01	1	200	3.98	36,160	9,086	350
N-28-Cu-31	278	2.10	1.98	1.99	1	225	4.16	21,440	5,156	565
N-28-Cu-32	285	2.09	2.03	2.03	1	250	4.24	29,550	6,965	402
N-28-Cu-33	271	2.03	2.02	2.00	1	275	4.10	29,910	7,294	411

N-28-Cu-30	283	2.03	2.09	2.01	1	300	4.24	22,180	5,228	536
N-90-Cu-1	280	1.99	1.97	2.02	1	100	3.92	32,730	8,349	393
N-90-Cu-2	300	2.02	1.99	2.01	1	125	4.02	41,280	10,269	304
N-90-Cu-3	301	2.03	2.01	2.01	1	150	4.08	29,160	7,147	424
N-90-Cu-4	296	1.98	2.01	2.03	1	175	3.98	39,800	10,001	318
N-90-Cu-5	273	1.97	2.02	2.01	1	200	3.98	34,410	8,647	368
N-90-Cu-6	293	2.00	1.99	2.00	1	225	3.98	39,380	9,894	322
N-90-Cu-7	270	1.98	2.00	1.94	1	250	3.96	35,250	8,902	361
N-90-Cu-8	273	1.98	2.01	1.99	1	275	3.98	26,140	6,568	485
N-90-Cu-9	293	2.03	2.00	2.00	1	300	4.06	26,850	6,613	462
		Height	Diameter							
U-28-Cy-6	98	2.08	1.19		1	200	1.11	27,730	24,933	688
U-28-Cy-7	92	2.01	1.19		1	200	1.11	24,070	21,642	793
U-28-Cy-8	95	2.08	1.19		1	200	1.11	28,340	25,482	673
U-28-Cy-8	94	2.06	1.19		1	200	1.11	19,700	17,713	969

U-28-Cy-10	94	2.06	1.19		1	200	1.11	26,060	23,432	732
U-28-Cy-21	97	2.10	1.19		1	100	1.11	27,240	24,493	701
U-28-Cy-22	96	2.08	1.19		1	125	1.11	23,320	20,968	818
U-28-Cy-23	96	2.10	1.19		1	150	1.11	19,500	17,533	979
U-28-Cy-24	92	2.03	1.19		1	175	1.11	30,550	27,469	625
U-28-Cy-25	90	2.03	1.19		1	200	1.11	27,060	24,331	705
U-28-Cy-26	93	2.01	1.19		1	225	1.11	27,130	24,394	703
U-28-Cy-27	95	2.06	1.19		1	250	1.11	23,200	20,860	823
U-28-Cy-28	91	2.11	1.19		1	275	1.11			
U-28-Cy-29	94	2.14	1.19		1	300	1.11	27,780	24,978	687
U-90-Cy-1	95	2.09	1.19		1	100	1.11	25,590	23,009	746
U-90-Cy-2	94	2.06	1.19		1	125	1.11	31,360	28,197	609
U-90-Cy-3	90	1.99	1.19		1	150	1.11	23,420	21,058	815
U-90-Cy-4	96	2.09	1.19		1	175	1.11	22,000	19,781	867
U-90-Cy-5	94	2.06	1.19		1	200	1.11	24,350	21,894	784

U-90-Cy-6	92	2.00	1.19		1	225	1.11	31,280	28,125	610
U-90-Cy-7	92	2.03	1.19		1	250	1.11	25,930	23,315	736
U-90-Cy-8	92	2.04	1.19		1	275	1.11	32,850	29,537	581
U-90-Cy-9	92	2.08	1.19		1	300	1.11	30,430	27,361	627
N-28-Cy-1	77	1.95	1.19		1	100	1.11	5,680	5,107	474
N-28-Cy-2	78	1.97	1.19		1	125	1.11	1,600	1,439	1,682
N-28-Cy-3	71	1.88	1.19		1	150	1.11	6,770	6,087	397
N-28-Cy-4	74	1.93	1.19		1	175	1.11	5,700	5,125	472
N-28-Cy-5	71	1.88	1.19		1	200	1.11	6,100	5,485	441
N-28-Cy-6	75	1.95	1.19		1	225	1.11	6,780	6,096	397
N-28-Cy-7	72	1.93	1.17		1	250	1.08	4,110	3,823	677
N-28-Cy-8	73	1.94	1.19		1	275	1.11	6,260	5,629	430
N-28-Cy-9	69	1.89	1.18		1	300	1.09	5,480	5,011	499
N-90-Cy-1	77	1.98	1.19		1	100	1.11	1,000	899	2,691

N-90-Cy-2	74	1.92	1.19		1	125	1.11	8,310	7,472	324
N-90-Cy-3	73	1.93	1.19		1	150	1.11	7,580	6,816	355
N-90-Cy-4	75	1.95	1.19		1	175	1.11	7,070	6,357	381
N-90-Cy-5	73	1.93	1.19		1	200	1.11	5,460	4,909	493
N-90-Cy-6	74	1.93	1.19		1	225	1.11	6,660	5,988	404
N-90-Cy-7	72	1.88	1.18		1	250	1.09	7,040	6,438	389
N-90-Cy-8	75	1.93	1.19		1	275	1.11	5,400	4,855	498
N-90-Cy-9	69	1.87	1.19		1	300	1.11	6,300	5,665	427

EXP 1 - INL										
Label	Post Heat				Experiment #	Temperature	Surface Area (in^2)	Loading at Failure		
	Weight	Height	Width	Depth				Pounds	PSI	Error
U-28-Cy-1	92	1.97	1.19		1-INL	200	1.11	27,290	24,538	699
U-28-Cy-2	97	2.09	1.19		1-INL	200	1.11	15,000	13,487	1,272
U-28-Cy-3	93	2.05	1.19		1-INL	200	1.11	18,200	16,364	1,049
U-28-Cy-4	93	2.06	1.19		1-INL	200	1.11	27,500	24,726	694

U-28-Cy-5	95	2.06	1.19		1-INL	200	1.11	17,800	16,005	1,072
U-28-Cy-11	94	2.06	1.19		1-INL	0	1.11	18,240	16,432	1,048
U-28-Cy-12	95	2.1	1.19		1-INL	0	1.11	21,020	18,937	910
U-28-Cy-13	95	2.08	1.19		1-INL	0	1.11	16,010	14,423	1,194
U-28-Cy-14	96	2.06	1.19		1-INL	0	1.11	21,600	19,459	885
U-28-Cy-15	91	2.03	1.19		1-INL	0	1.11	24,230	21,829	789
N-28-Cy-10	74	1.94	1.19		1-INL	200	1.11	5,850	5,260	460
N-28-Cy-11	75	1.96	1.19		1-INL	200	1.11	5,480	4,927	491
N-28-Cy-12	73	1.86	1.19		1-INL	200	1.11	6,180	5,557	435
N-28-Cy-13	78	1.96	1.19		1-INL	200	1.11	3,210	2,935	853
N-28-Cy-14	76	1.93	1.19		1-INL	200	1.11	5,400	4,855	498
N-28-Cy-15	77	1.94	1.19		1-INL	0	1.11	7,940	7,139	339
N-28-Cy-16	76	1.95	1.19		1-INL	0	1.11	6,980	6,276	386
N-28-Cy-17	78	2	1.19		1-INL	0	1.11	3,250	2,922	828
N-28-Cy-18	75	1.92	1.19		1-INL	0	1.11	3,880	3,489	694
N-28-Cy-19	76	1.94	1.19		1-INL	0	1.11	4,260	3,830	632
U-28-Cu-1	346	2.08	2.01	2.07	1-INL	200	4.16	72,376	17,398	1,935

U-28-Cu-3	333	2.01	2.02	2.01	1-INL	200	4.06	105,004	25,863	1,366
U-28-Cu-5	341	2.12	2.00	2.01	1-INL	0	4.02	65,293	16,242	2,219
U-28-Cu-7	340	2.07	2.05	2.00	1-INL	0	4.10	79,070	24,665	2,298
N-28-Cu-6	295	2.03	2.00	1.99	1-INL	0	3.98	33,780	8,487	375
N-28-Cu-7	292	2.03	1.98	2.01	1-INL	200	4.00	44,550	11,138	283
N-28-Cu-8	306	2.00	2.01	2.04	1-INL	0	4.10	30,540	7,448	403
N-28-Cu-9	289	2.01	2.01	1.99	1-INL	200	4.00	32,510	8,128	388

EXP 2											
Label	Post Heat				Experiment #	Temperature	Surface Area (in^2)	Loading at Failure		Time at T1	Error (psi
	Weight	Height	Width	Depth				Pounds	PSI		
U-28-Cu-47	347	2.21	2.01	2.00	2	100	4.44	82,410	18,552	1	1,591
U-28-Cu-19	332	2.00	2.06	2.00	2	125	4.12	120,450	29,235	1	1,174
U-28-Cu-20	331	2.02	2.04	2.01	2	150	4.12	94,190	22,857	1	1,501
U-28-Cu-21	335	2.09	2.00	2.03	2	175	4.18	121,460	29,057	1	1,147
U-28-Cu-18	332	2.02	2.00	2.07	2	200	4.04	106,170	26,280	1	1,358

U-28-Cu-40	354	2.17	2.04	2.02	2	225	4.43	87,660	19,802	1	1,501
U-28-Cu-22	331	2.07	2.02	2.02	2	100	4.18	117,100	28,005	2	1,190
U-28-Cu-23	340	2.02	2.09	2.05	2	125	4.22	127,480	30,196	2	1,082
U-28-Cu-24	333	2.03	1.99	2.06	2	150	4.04	101,410	25,103	2	1,422
U-28-Cu-25	329	2.02	2.01	2.02	2	175	4.06	95,220	23,452	2	1,507
U-28-Cu-39	339	2.20	2.00	1.99	2	200	4.40	67,920	15,436	2	1,949
U-28-Cu-41	335	2.08	2.00	1.99	2	225	4.16	96,530	23,204	2	1,450
U-28-Cu-26	333	2.01	2.05	2.03	2	100	4.12	130,750	31,732	4	1,081
U-28-Cu-27	337	2.01	2.06	2.04	2	125	4.14	133,490	32,239	4	1,054
U-28-Cu-28	336	2.02	2.02	2.05	2	150	4.08	110,830	27,162	4	1,288
U-28-Cu-29	333	2.01	2.09	2.00	2	175	4.20	125,060	29,770	4	1,109
U-28-Cu-42	353	2.23	2.02	1.99	2	200	4.50	82,180	18,244	4	1,573
U-28-Cu-44	368	2.25	2.03	2.02	2	225	4.57	85,870	18,800	4	1,485
U-28-Cu-30	358	2.17	2.02	2.03	2	100	4.38	79,070	18,039	8	1,680
U-28-Cu-31	354	2.25	2.02	2.02	2	125	4.55	92,590	20,372	8	1,384

U-28-Cu-32	357	2.26	2.01	2.02	2	150	4.54	61,610	13,563	8	2,081
U-28-Cu-33	352	2.15	2.02	2.03	2	175	4.34	84,620	19,484	8	1,585
U-28-Cu-43	352	2.18	2.02	2.01	2	200	4.40	108,060	24,539	8	1,224
U-28-Cu-45	331	1.07	2.01	1.99	2	225	2.15	79,210	36,830	8	3,419
U-28-Cu-34	347	2.21	1.99	2.01	2	100	4.40	62,600	14,234	12	2,116
U-28-Cu-35	347	2.12	2.03	2.03	2	125	4.30	76,840	17,855	12	1,761
U-28-Cu-36	359	2.22	2.04	2.04	2	150	4.53	114,830	25,356	12	1,120
U-28-Cu-37	354	2.21	2.05	2.01	2	175	4.53	79,360	17,517	12	1,620
U-28-Cu-38	342	2.12	1.99	2.01	2	200	4.22	80,160	19,001	12	1,722
U-28-Cu-46	341	2.15	2.02	2.01	2	225	4.34	102,150	23,521	12	1,313

N-28-Cu-10	298	2.06	1.98	2.03	2	100	4.08	28,160	6,904	1	439
N-28-Cu-11	277	1.96	2.01	2.01	2	125	3.94	22,790	5,785	1	561
N-28-Cu-12	284	2.04	1.93	2.03	2	150	3.94	25,990	6,601	1	493
N-28-Cu-13	282	2.04	2.06	1.94	2	175	4.20	31,530	7,503	1	380

N-28-Cu-34	274	2.03	2.01	2.03	2	200	4.08	27,500	6,740	1	449
N-28-Cu-36	281	2.01	2.12	2.01	2	225	4.26	29,460	6,914	1	402
N-28-Cu-14	302	2.00	2.04	2.05	2	100	4.08	21,700	5,319	2	569
N-28-Cu-15	277	2.03	1.92	2.03	2	125	3.90	23,650	6,068	2	547
N-28-Cu-16	277	1.93	2.03	2.00	2	150	3.92	22,820	5,825	2	564
N-28-Cu-17	280	1.92	2.04	2.06	2	175	3.92	23,470	5,992	2	548
N-28-Cu-35	273	1.99	2.02	2.06	2	200	4.02	26,680	6,637	2	470
N-28-Cu-37	275	2.06	2.00	1.99	2	225	4.12	30,930	7,507	2	396
N-28-Cu-18	272	2.01	2.00	1.90	2	100	4.02	35,840	8,915	4	350
N-28-Cu-19	272	2.03	1.95	2.03	2	125	3.96	23,090	5,833	4	552
N-28-Cu-20	281	2.03	1.99	1.95	2	150	4.04	34,390	8,513	4	363
N-28-Cu-21	282	2.00	2.01	1.98	2	175	4.02	31,090	7,734	4	403
N-28-Cu-38	277	2.03	2.08	2.01	2	200	4.22	29,760	7,048	4	401
N-28-Cu-40	278	2.07	2.00	2.00	2	225	4.14	33,790	8,162	4	360
N-28-Cu-22	279	1.96	2.00	2.01	2	100	3.92	8,700	2,219	8	1,478

N-28-Cu-23	286	1.96	2.00	2.02	2	125	3.92	27,650	7,054	8	465
N-28-Cu-24	283	1.96	2.02	2.02	2	150	3.96	8,600	2,172	8	1,481
N-28-Cu-25	278	1.98	2.01	2.02	2	175	3.98	28,550	7,174	8	444
N-28-Cu-39	275	2.09	2.00	1.97	2	200	4.18	25,590	6,122	8	471
N-28-Cu-41	274	2.11	2.00	2.00	2	225	4.22	27,160	6,436	8	440
N-28-Cu-26	285	1.94	2.02	2.03	2	100	3.92	23,840	6,083	12	540
N-28-Cu-27	276	2.03	2.01	1.91	2	125	4.08	32,010	7,845	12	386
N-28-Cu-28	285	1.96	2.05	2.05	2	150	4.02	27,130	6,752	12	462
N-28-Cu-29	282	2.01	1.93	2.00	2	175	3.88	27,070	6,978	12	480
N-28-Cu-42	275	2.05	2.00	2.02	2	200	4.10	21,900	5,341	12	561
N-28-Cu-43	273	2.04	2.03	2.00	2	225	4.14	29,350	7,087	12	415

U-90-Cu-10	347	2.15	2.04	2.02	2	100	4.39	122,860	28,012	1	1,081
U-90-Cu-11	332	2.15	2.03	2.00	2	125	4.36	80,590	18,465	1	1,656
U-90-Cu-12	333	2.12	2.03	2.01	2	150	4.30	140,400	32,624	1	964

U-90-Cu-13	342	2.15	2.03	2.00	2	175	4.36	115,850	26,544	1	1,152
U-90-Cu-30	333	2.06	2.02	2.04	2	200	4.16	97,690	23,476	1	1,433
U-90-Cu-35	362	2.24	2.04	2.01	2	225	4.57	140,070	30,653	1	910
U-90-Cu-14	340	2.19	2.03	2.00	2	100	4.45	72,220	16,245	2	1,814
U-90-Cu-15	341	2.12	2.04	2.07	2	125	4.32	131,610	30,431	2	1,023
U-90-Cu-16	335	2.11	2.00	2.03	2	150	4.22	122,210	28,960	2	1,129
U-90-Cu-17	350	2.17	2.04	2.05	2	175	4.43	120,010	27,110	2	1,096
U-90-Cu-31	335	2.06	2.01	2.01	2	200	4.14	144,310	34,852	2	975
U-90-Cu-36	343	2.08	2.01	2.05	2	225	4.18	128,490	30,733	2	1,084
U-90-Cu-18	345	2.13	2.06	2.04	2	100	4.39	134,500	30,653	4	987
U-90-Cu-19	333	2.11	2.02	2.05	2	125	4.26	113,000	26,512	4	1,209
U-90-Cu-20	328	2.01	2.04	2.05	2	150	4.10	138,580	33,797	4	1,025
U-90-Cu-21	327	2.04	2.00	2.02	2	175	4.08	95,320	23,363	4	1,498
U-90-Cu-32	348	2.20	2.00	2.01	2	200	4.40	81,690	18,566	4	1,620
U-90-Cu-37	341	2.11	2.01	2.01	2	225	4.24	148,260	34,958	4	926

U-90-Cu-22	329	2.06	2.04	2.00	2	100	4.20	83,960	19,979	8	1,651
U-90-Cu-23	332	2.13	2.01	2.00	2	125	4.28	84,600	19,760	8	1,608
U-90-Cu-24	336	2.13	2.01	2.00	2	150	4.28	85,510	19,973	8	1,591
U-90-Cu-25	329	2.02	2.03	2.03	2	175	4.10	76,540	18,666	8	1,856
U-90-Cu-33	352	2.13	2.03	2.02	2	200	4.32	142,360	32,924	8	946
U-90-Cu-38	345	2.15	2.03	2.00	2	225	4.36	150,770	34,545	8	885
U-90-Cu-26	340	2.14	2.02	2.05	2	100	4.32	71,840	16,619	12	1,876
U-90-Cu-27	331	2.11	2.01	2.01	2	125	4.24	125,960	29,700	12	1,090
U-90-Cu-28	340	2.07	2.06	2.04	2	150	4.26	102,430	24,021	12	1,334
U-90-Cu-29	344	2.14	2.04	2.01	2	175	4.37	100,790	23,087	12	1,324
U-90-Cu-34	345	2.16	2.00	2.03	2	200	4.32	139,100	32,199	12	969
U-90-Cu-39	352	2.18	2.05	2.01	2	225	4.47	133,080	29,778	12	979

N-90-Cu-10	286	2.04	2.04	2.02	2	100	4.16	24,040	5,777	1	504
N-90-Cu-11	268	1.90	2.03	2.01	2	125	3.86	27,580	7,151	1	474

N-90-Cu-12	278	2.00	2.02	1.99	2	150	4.04	39,710	9,829	1	314
N-90-Cu-13	303	2.05	2.00	2.04	2	175	4.10	22,710	5,539	1	541
N-90-Cu-30	283	2.07	2.02	2.00	2	200	4.18	41,210	9,856	1	293
N-90-Cu-35	280	2.06	2.01	2.01	2	225	4.14	25,950	6,267	1	469
N-90-Cu-14	277	1.99	2.01	2.03	2	100	4.00	33,140	8,285	2	380
N-90-Cu-15	296	2.12	2.02	2.03	2	125	4.28	32,590	7,610	2	361
N-90-Cu-16	291	2.05	2.03	2.02	2	150	4.16	35,350	8,495	2	343
N-90-Cu-17	297	2.13	2.01	2.03	2	175	4.28	25,040	5,849	2	470
N-90-Cu-31	269	1.93	2.00	1.98	2	200	3.86	27,580	7,145	2	474
N-90-Cu-36	292	2.04	2.03	2.00	2	225	4.14	34,830	8,411	2	349
N-90-Cu-18	288	2.10	2.03	1.96	2	100	4.26	33,780	7,924	4	350
N-90-Cu-19	308	2.14	2.02	2.06	2	125	4.32	28,350	6,558	4	411
N-90-Cu-20	274	2.00	2.01	2.03	2	150	4.02	23,550	5,858	4	532
N-90-Cu-21	287	2.08	2.03	2.03	2	175	4.22	30,210	7,155	4	395
N-90-Cu-32	302	2.15	2.01	2.01	2	200	4.32	37,560	8,691	4	311

N-90-Cu-37	279	2.10	2.00	2.00	2	225	4.20	20,410	4,860	4	588
N-90-Cu-22	292	2.02	2.00	2.00	2	100	4.04	40,290	9,973	8	310
N-90-Cu-23	281	2.02	2.01	2.01	2	125	4.06	33,770	8,317	8	368
N-90-Cu-24	286	2.08	2.03	2.01	2	150	4.22	23,170	5,487	8	515
N-90-Cu-25	300	2.06	2.02	2.05	2	175	4.16	34,760	8,353	8	349
N-90-Cu-33	290	2.02	2.01	2.00	2	200	4.06	43,300	10,664	8	287
N-90-Cu-38	301	2.05	2.00	2.02	2	225	4.10	28,360	6,917	8	434
N-90-Cu-26	277	2.07	2.01	1.97	2	100	4.16	24,540	5,898	12	494
N-90-Cu-27	291	2.05	2.02	2.06	2	125	4.14	31,150	7,522	12	391
N-90-Cu-28	299	2.09	2.00	1.98	2	150	4.18	24,230	5,797	12	498
N-90-Cu-29	286	2.10	2.00	2.02	2	175	4.20	31,630	7,531	12	379
N-90-Cu-34	293	2.13	2.02	2.04	2	200	4.30	38,430	8,932	12	305
N-90-Cu-39	302	2.07	2.03	2.02	2	225	4.20	25,480	6,064	12	471

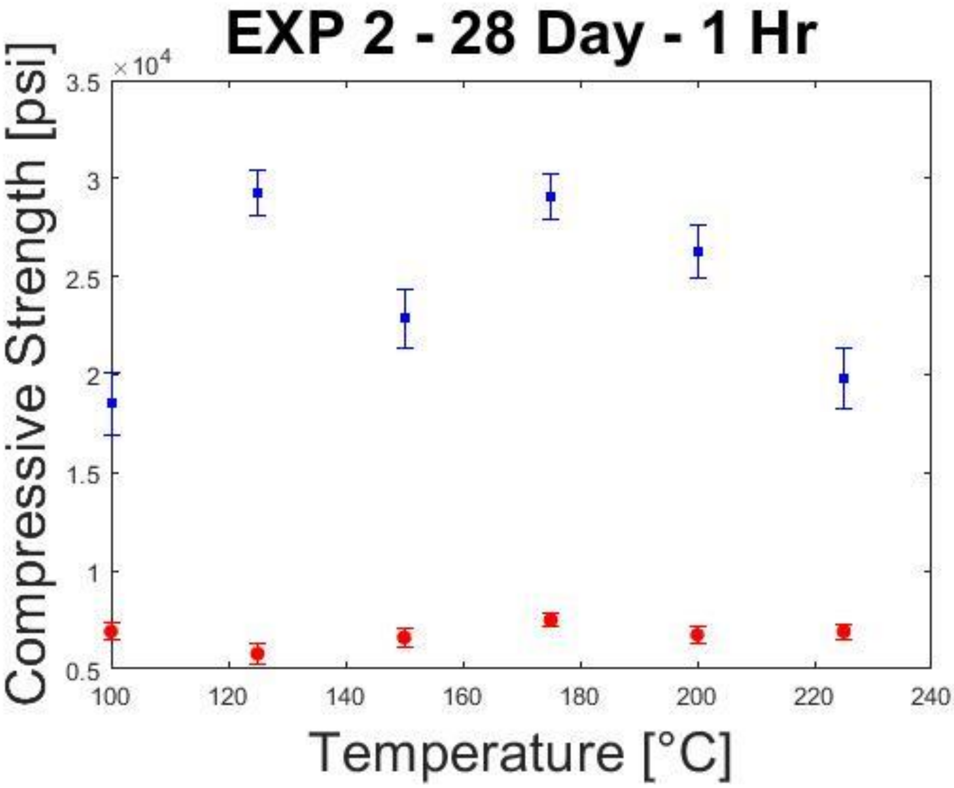
Appendix III – EXP 1 - INL Sample Dose Map

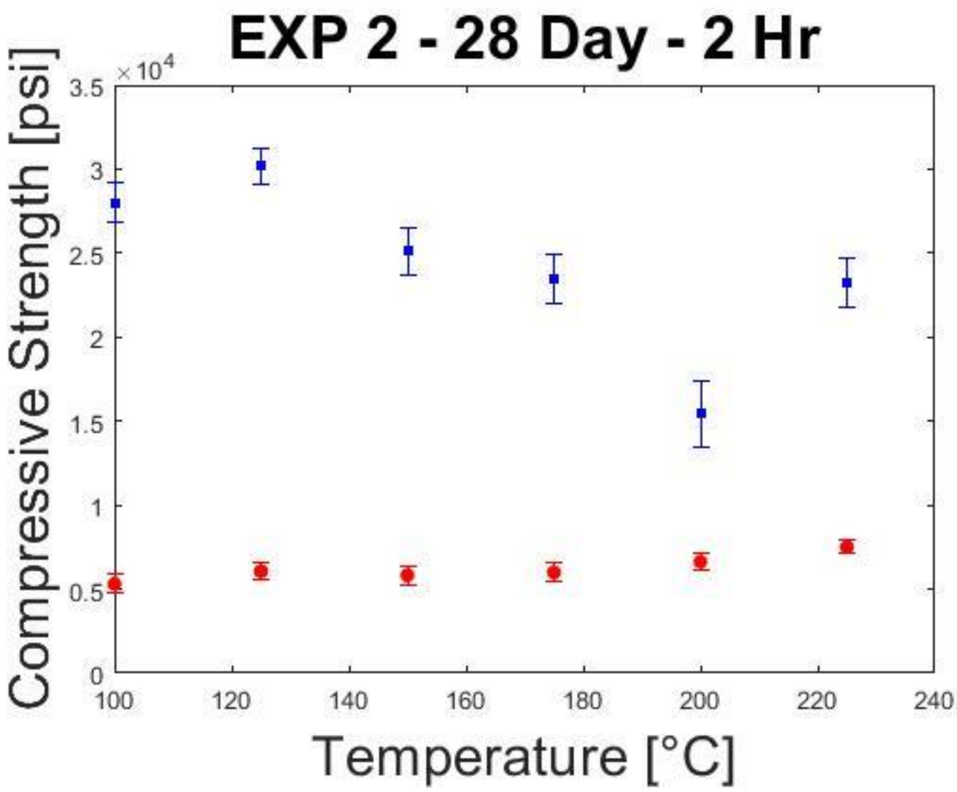
EXP 1 - INL			
Sample ID	INL Container	Weight (g)	Total Exposure (R)
U-28-Cu-1	1	377	3.45×10^7
U-28-Cu-7	2	371	4.54×10^7
U-28-Cu-3	3	364	5.45×10^7
U-28-Cu-5	4	373	6.25×10^7
U-28-Cy-1	5	367	6.87×10^7
U-28-Cy-2			
N-28-Cy-10			
N-28-Cy-11			
U-28-Cy-4	6	368	7.29×10^7
U-28-Cy-11			
N-28-Cy-12			
N-28-Cy-17			
U-28-Cy-13	7	375	7.52×10^7
U-28-Cy-14			
N-28-Cy-13			
N-28-Cy-14			
N-28-Cu-8	8	340	7.55×10^7
N-28-Cu-6	9	328	7.35×10^7
U-28-Cy-12	10	370	6.93×10^7
U-28-Cy-15			
N-28-Cy-15			
N-28-Cy-16			
U-28-Cy-3	11	372	6.34×10^7
U-28-Cy-5			
N-28-Cy-18			
N-28-Cy-19			
N-28-Cu-7	12	322	5.55×10^7
N-28-Cu-8	13	318	4.59×10^7

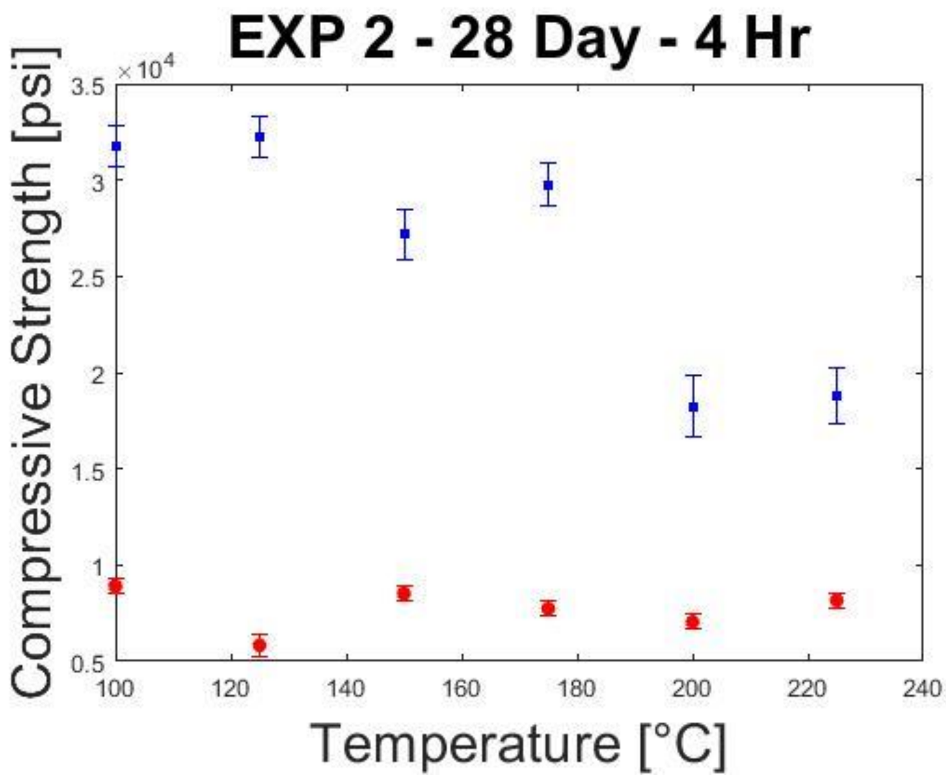
Appendix IV – Normal Concrete Mixture

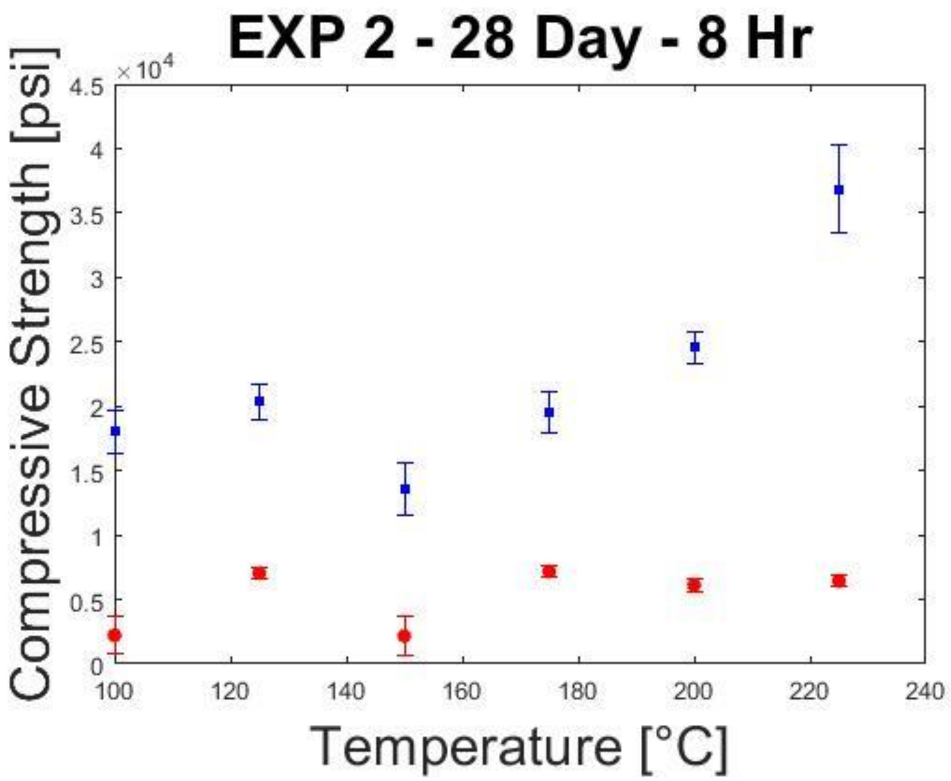
Material	Volume (ft^3)	Weight (lbs)
Cement	0.164835165	32.4
Fly Ash	0.055762534	8.1422
Fine Aggregate	0.45206659	75.6
Coarse Aggregate	0.247606471	36
Water	0.259615385	15.8
Total	1.179886145	168.3422

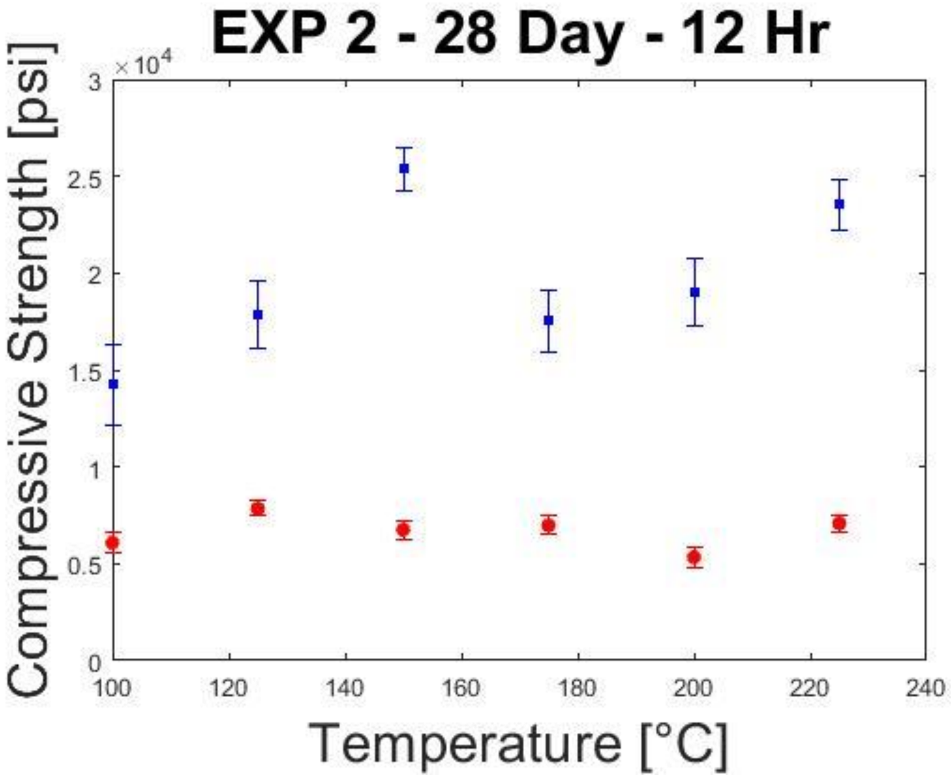
Appendix V – EXP 2 Individual Test Results

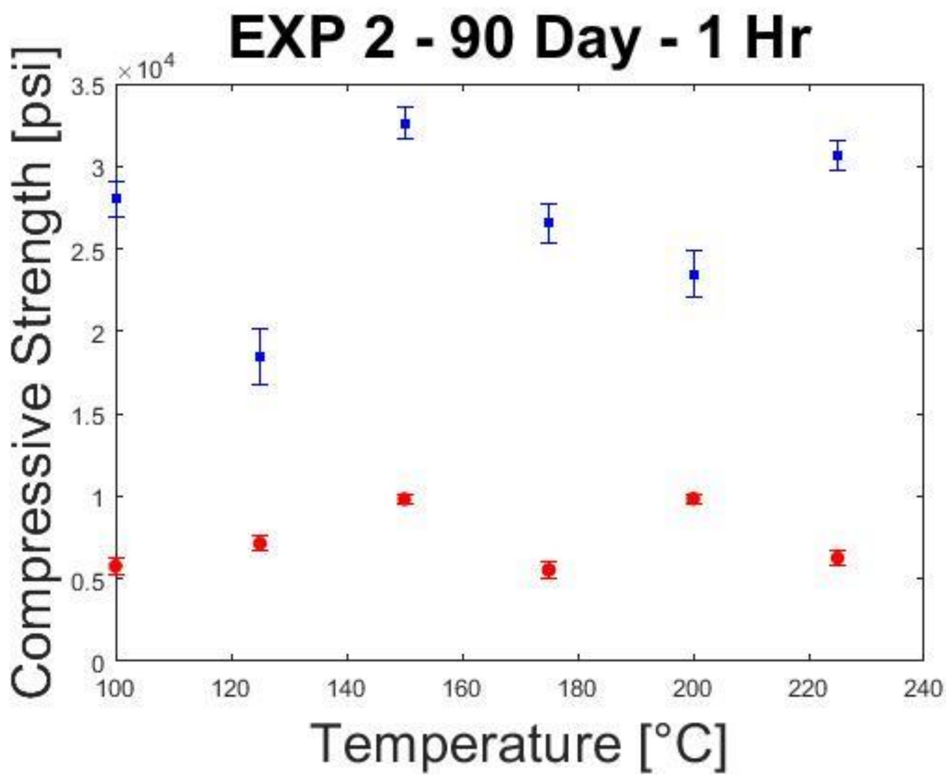


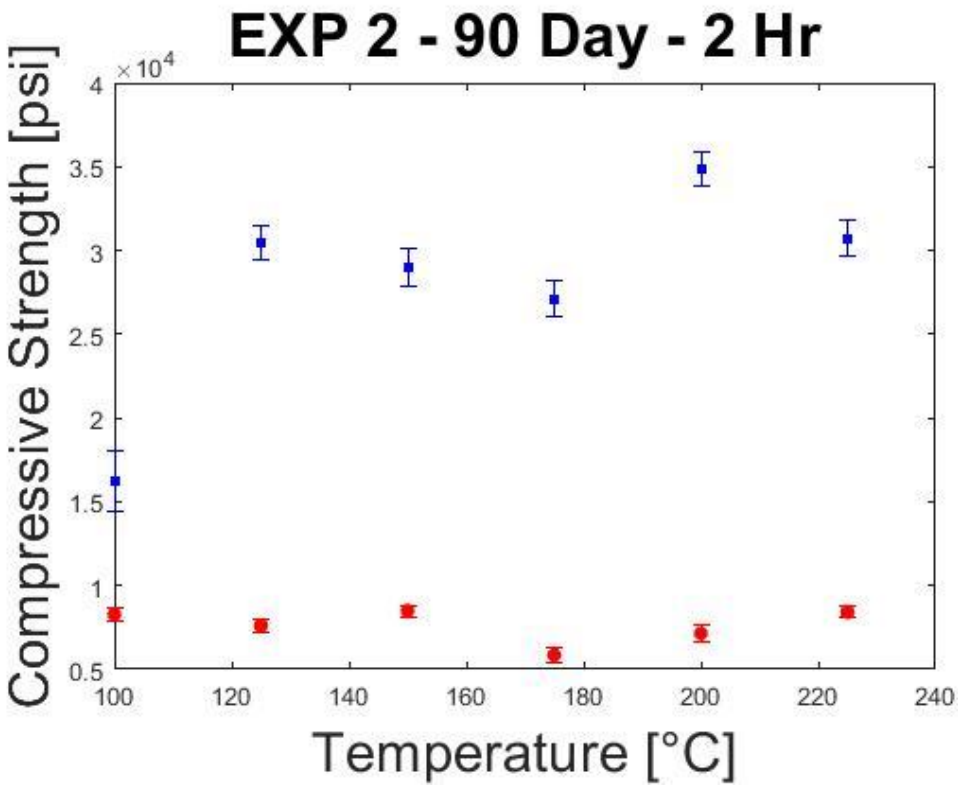

EXP 2 - 28 Day - 2 Hr
Compressive Strength [psi]
× 10^4
3.5
3
2.5
2
1.5
1
0.5
0
100
120
140
160
180
200
220
240
Temperature [°C]

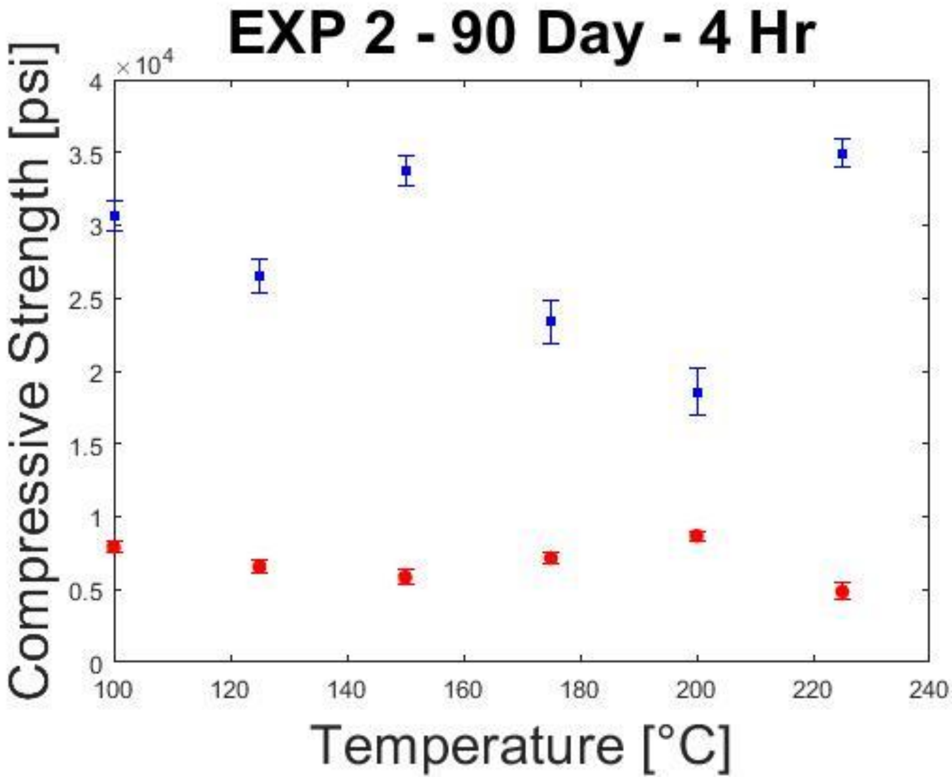

EXP 2 - 28 Day - 4 Hr
Compressive Strength [psi]
× 10^4
3.5
3
2.5
2
1.5
1
0.5
100
120
140
160
180
200
220
240
Temperature [°C]

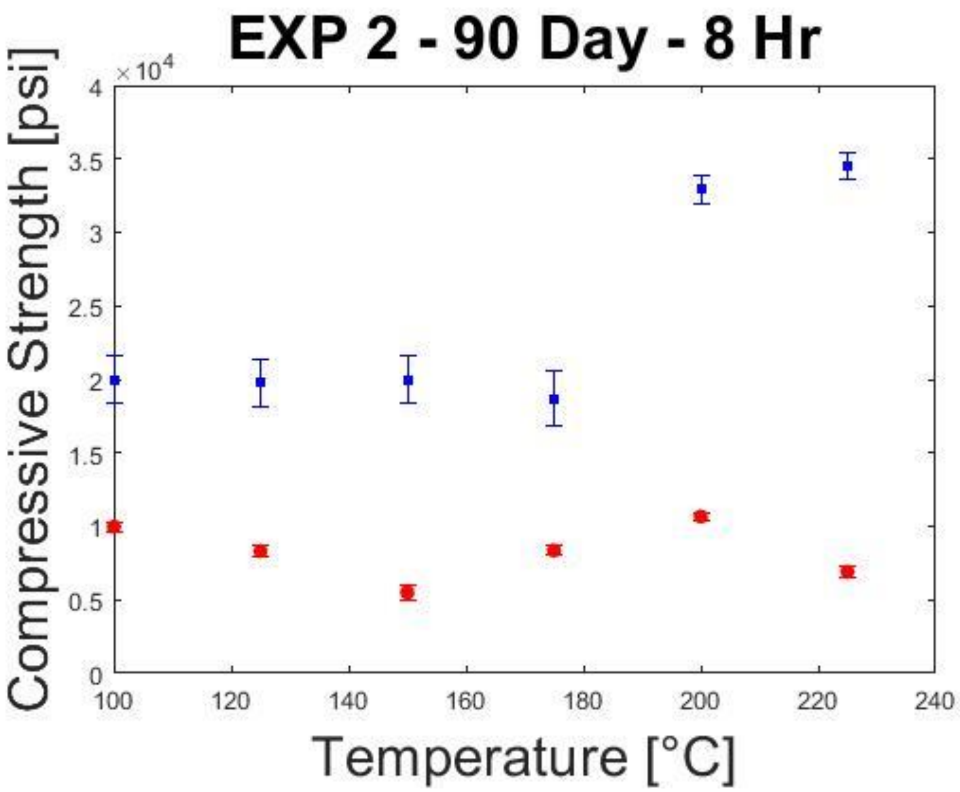

EXP 2 - 28 Day - 8 Hr
×10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Compressive Strength [psi]
100
120
140
160
180
200
220
240
Temperature [°C]

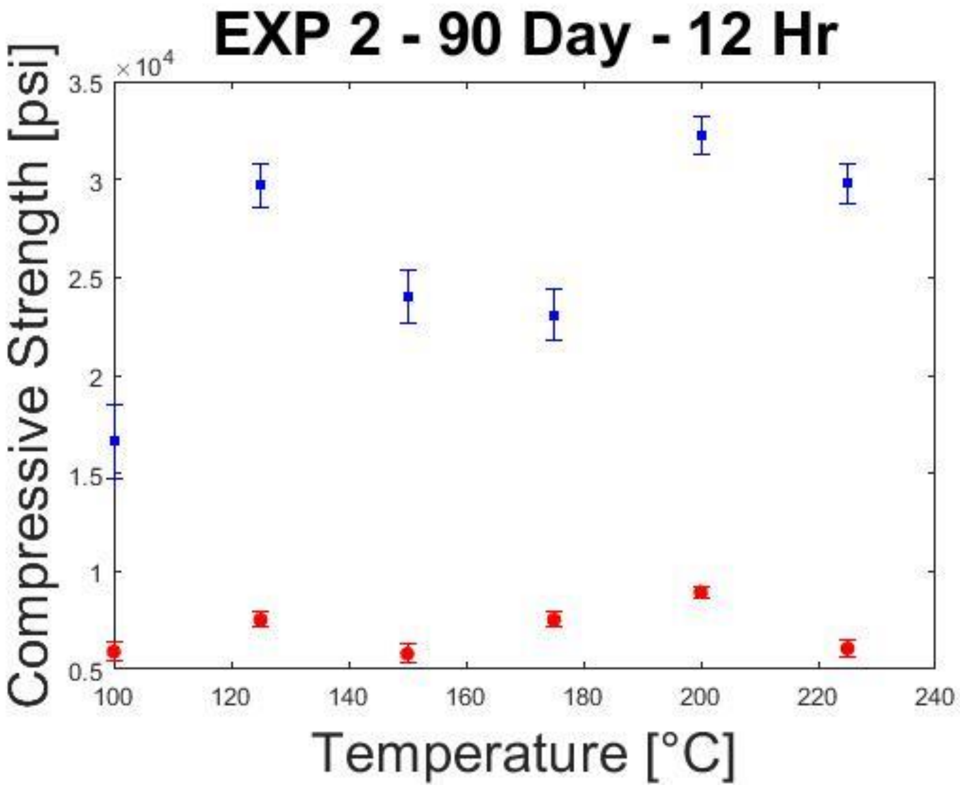

EXP 2 - 28 Day - 12 Hr
×10^4
3
2.5
2
1.5
1
0.5
0
Compressive Strength [psi]
100
120
140
160
180
200
220
240
Temperature [°C]

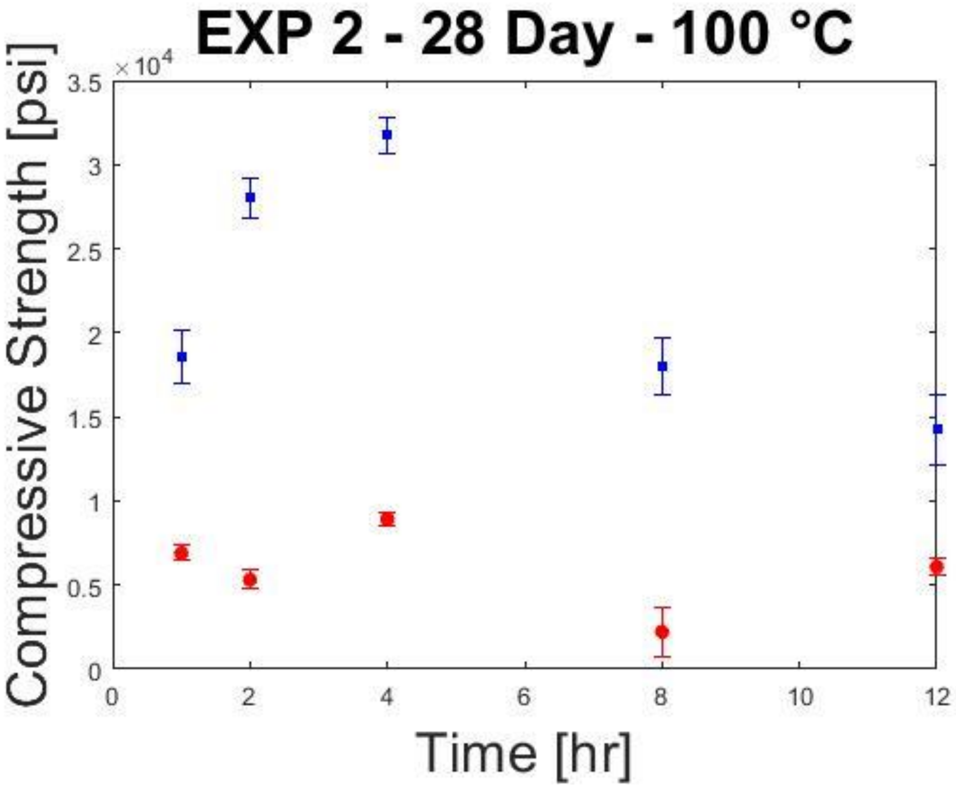

EXP 2 - 90 Day - 1 Hr
Compressive Strength [psi]
$\times 10^4$
3.5
3
2.5
2
1.5
1
0.5
0
100
120
140
160
180
200
220
240
Temperature [°C]

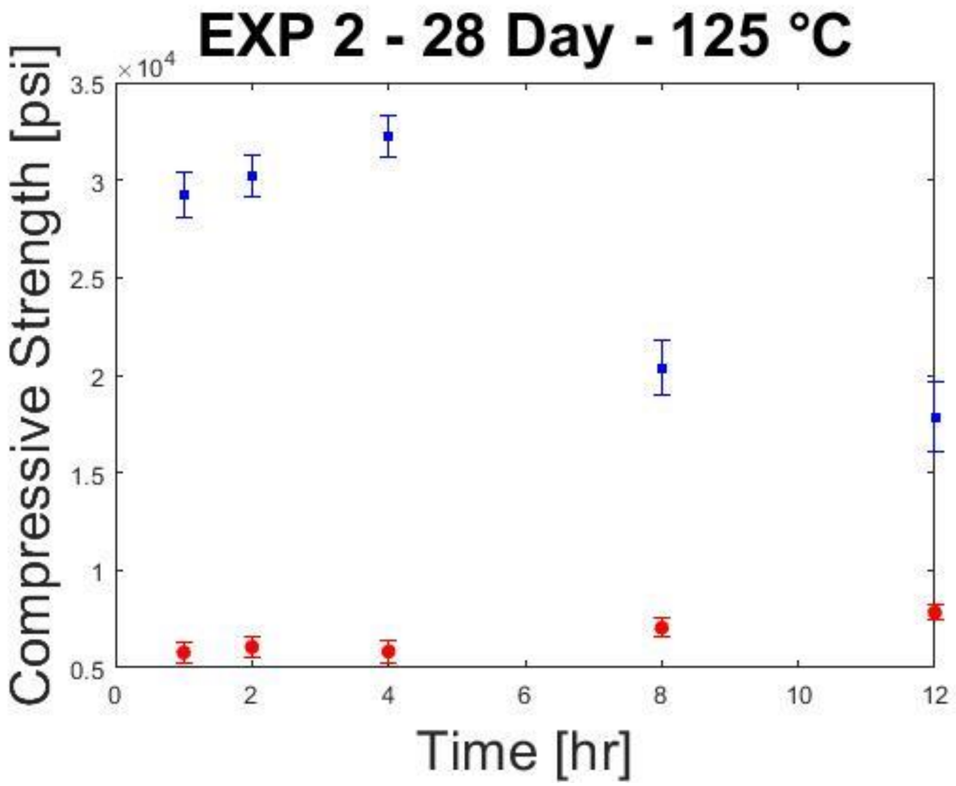

EXP 2 - 90 Day - 2 Hr
Compressive Strength [psi]
$\times 10^4$
4
3.5
3
2.5
2
1.5
1
0.5
100
120
140
160
180
200
220
240
Temperature [°C]

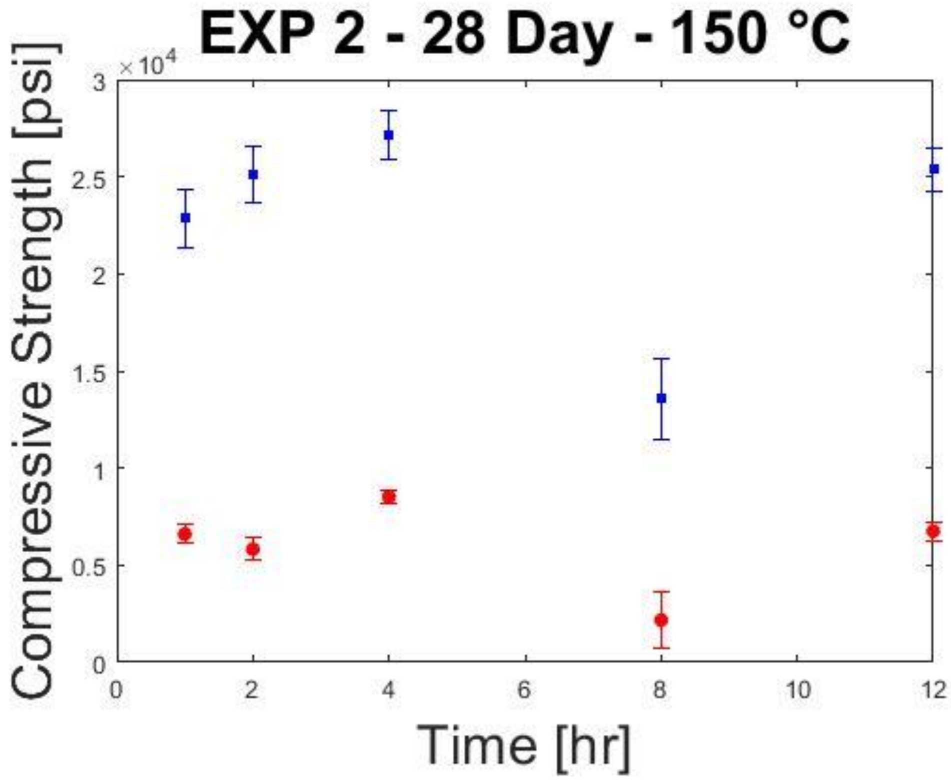

EXP 2 - 90 Day - 4 Hr
Compressive Strength [psi]
×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
100
120
140
160
180
200
220
240
Temperature [°C]

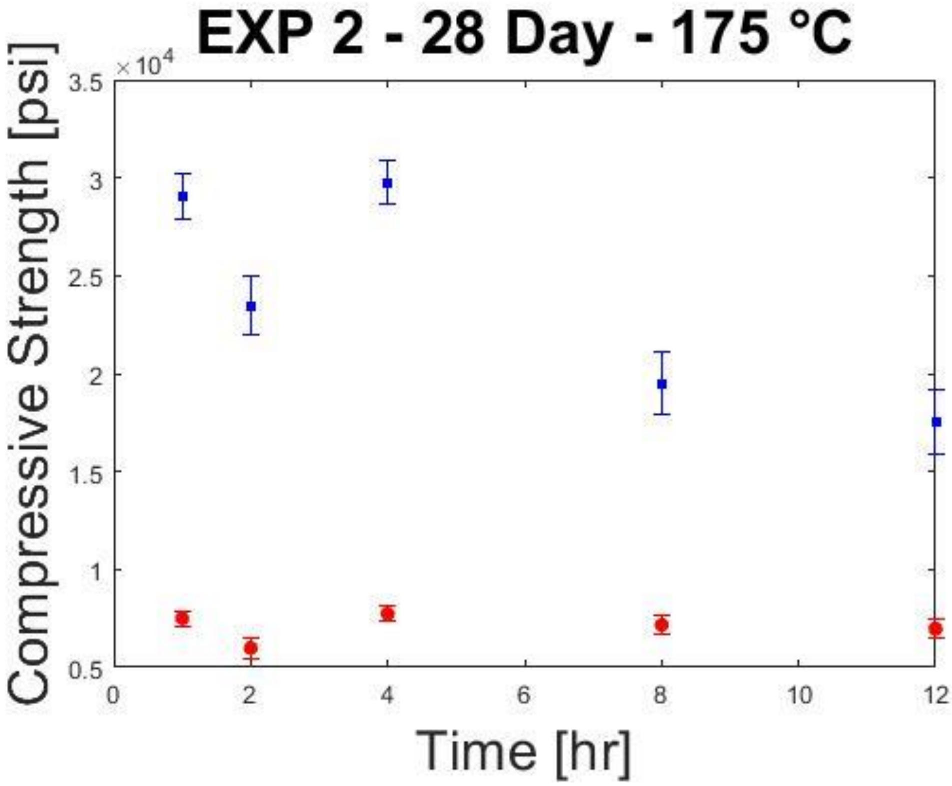

EXP 2 - 90 Day - 8 Hr
Compressive Strength [psi]
×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
100
120
140
160
180
200
220
240
Temperature [°C]

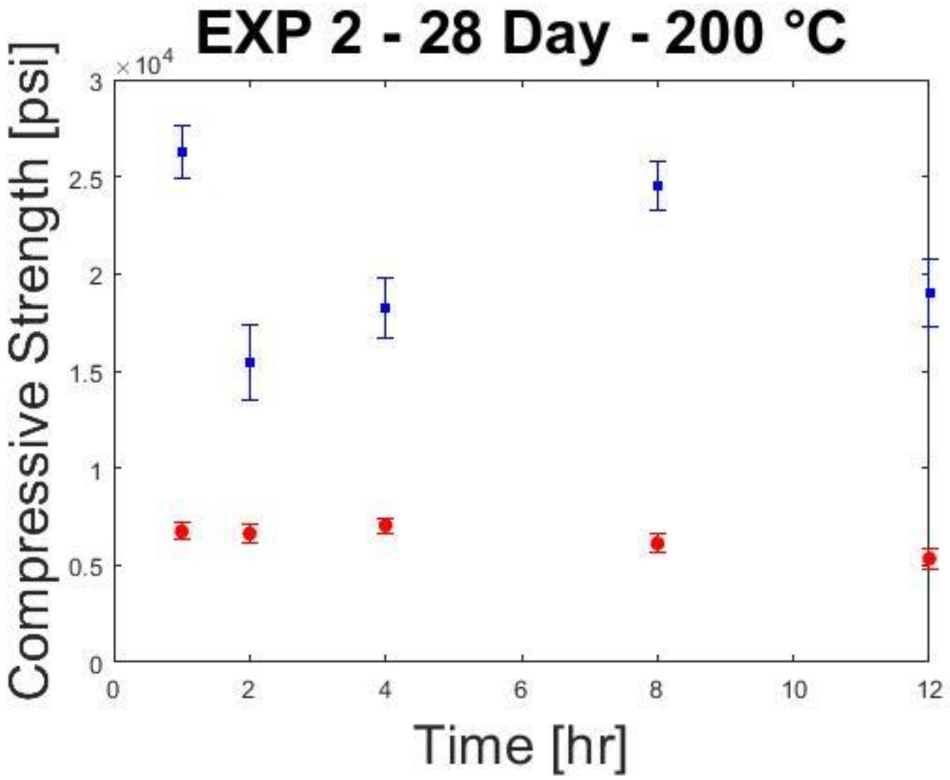

EXP 2 - 90 Day - 12 Hr
Compressive Strength [psi]
×10^4
3.5
3
2.5
2
1.5
1
0.5
100
120
140
160
180
200
220
240
Temperature [°C]

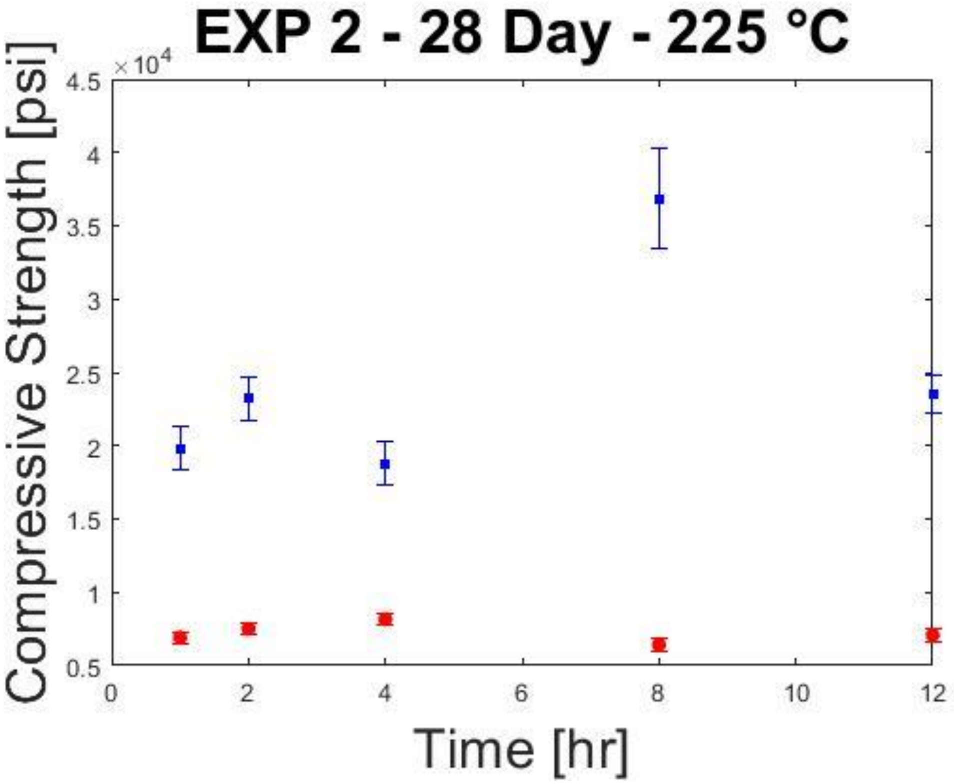

EXP 2 - 28 Day - 100 °C
Compressive Strength [psi]
Time [hr]
×10^4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12

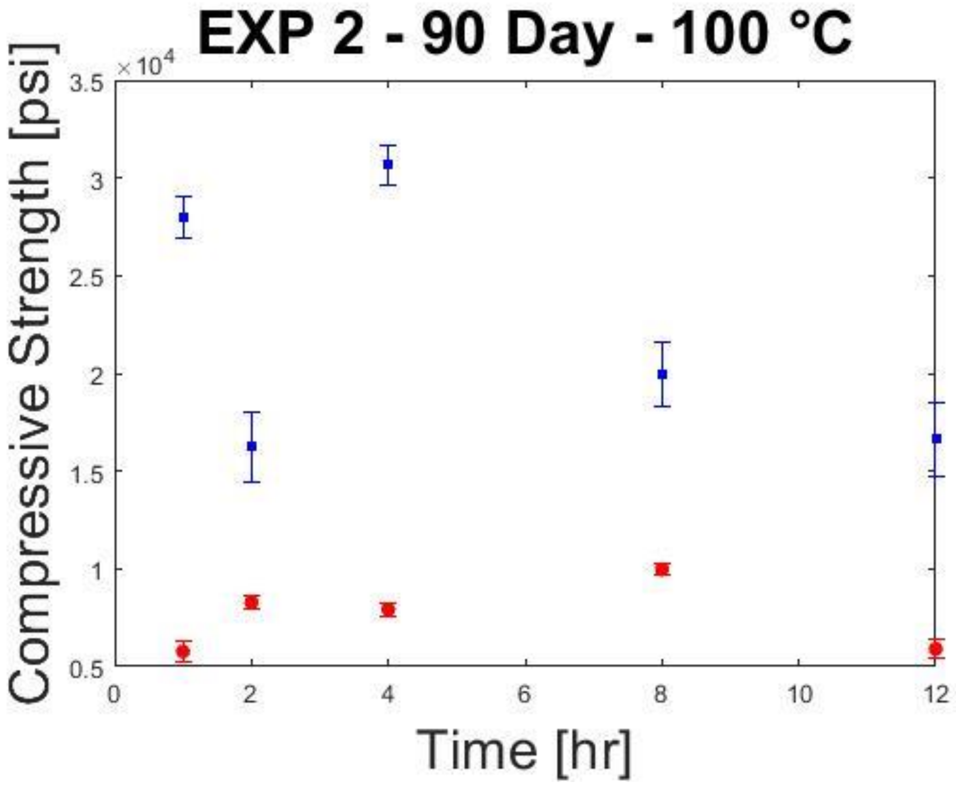

EXP 2 - 28 Day - 125 °C
Compressive Strength [psi]
Time [hr]
×10^4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12

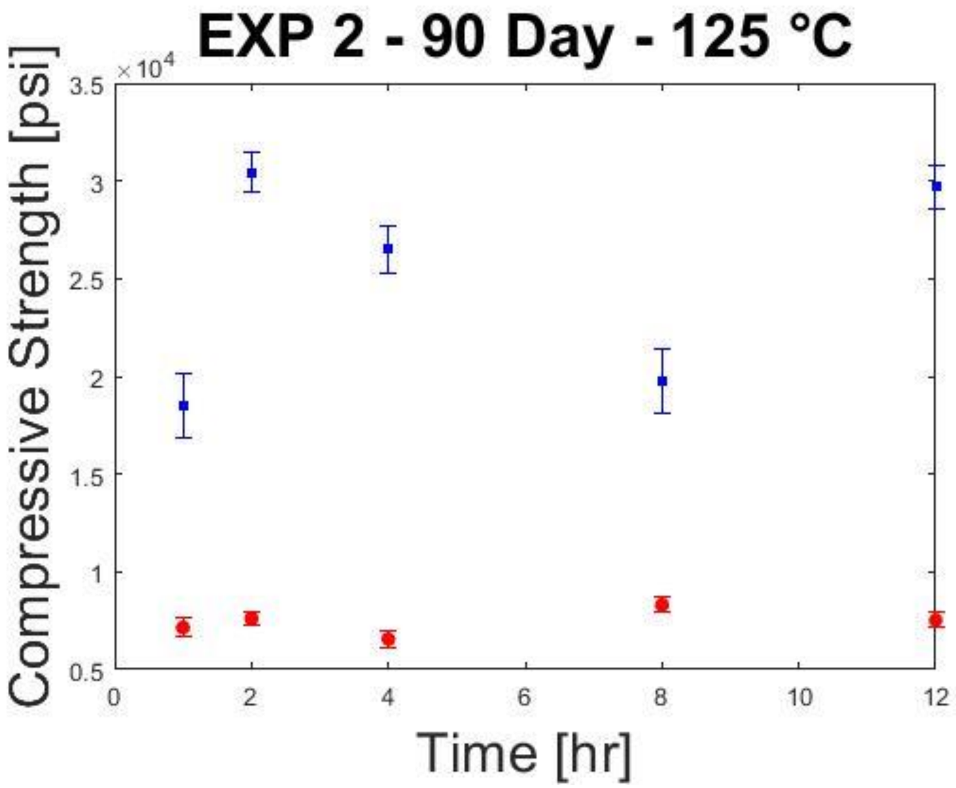

EXP 2 - 28 Day - 150 °C
Compressive Strength [psi]
$\times 10^4$
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
Time [hr]

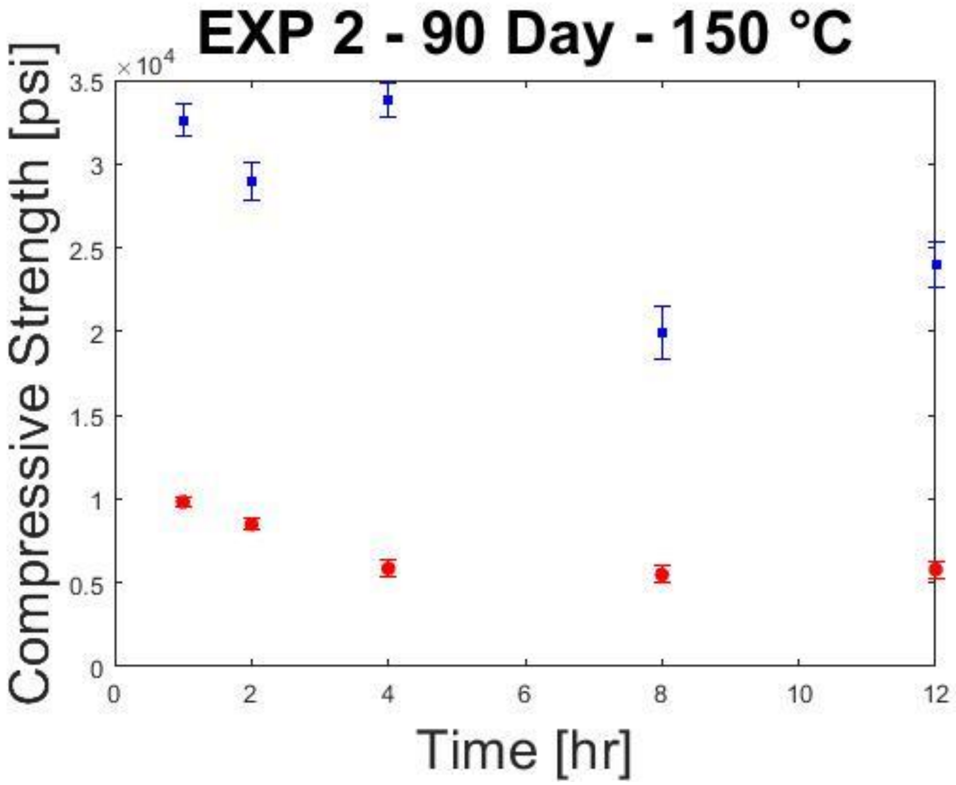

EXP 2 - 28 Day - 175 °C
Compressive Strength [psi]
$\times 10^4$
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
Time [hr]

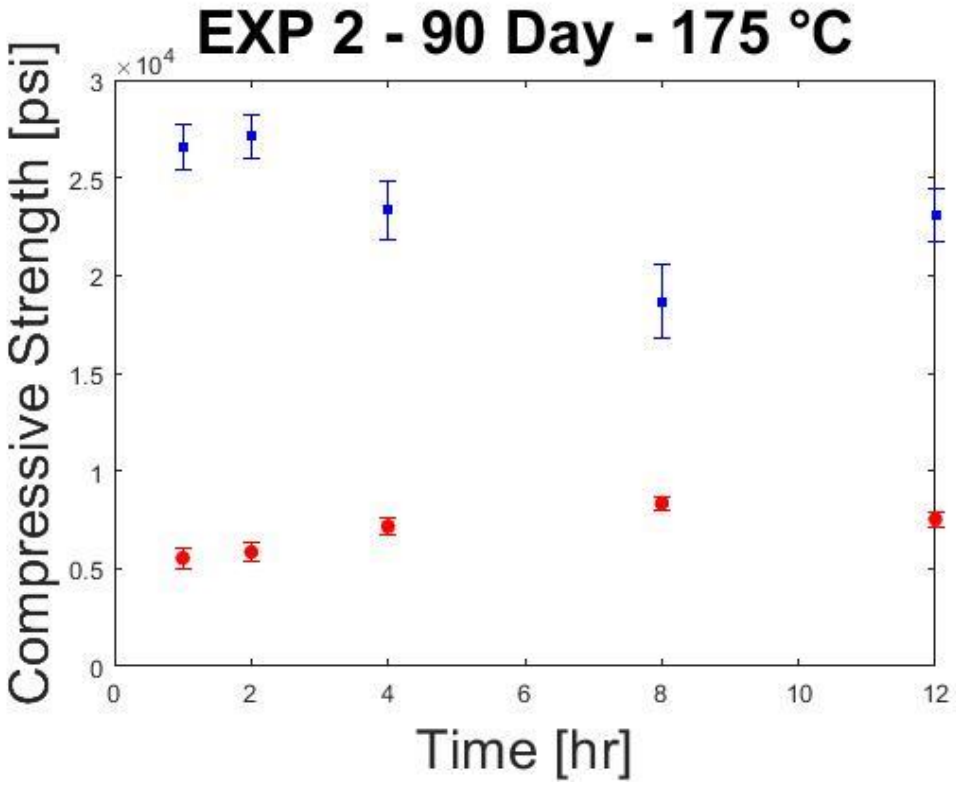

EXP 2 - 28 Day - 200 °C
Compressive Strength [psi]
×10^4
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
Time [hr]

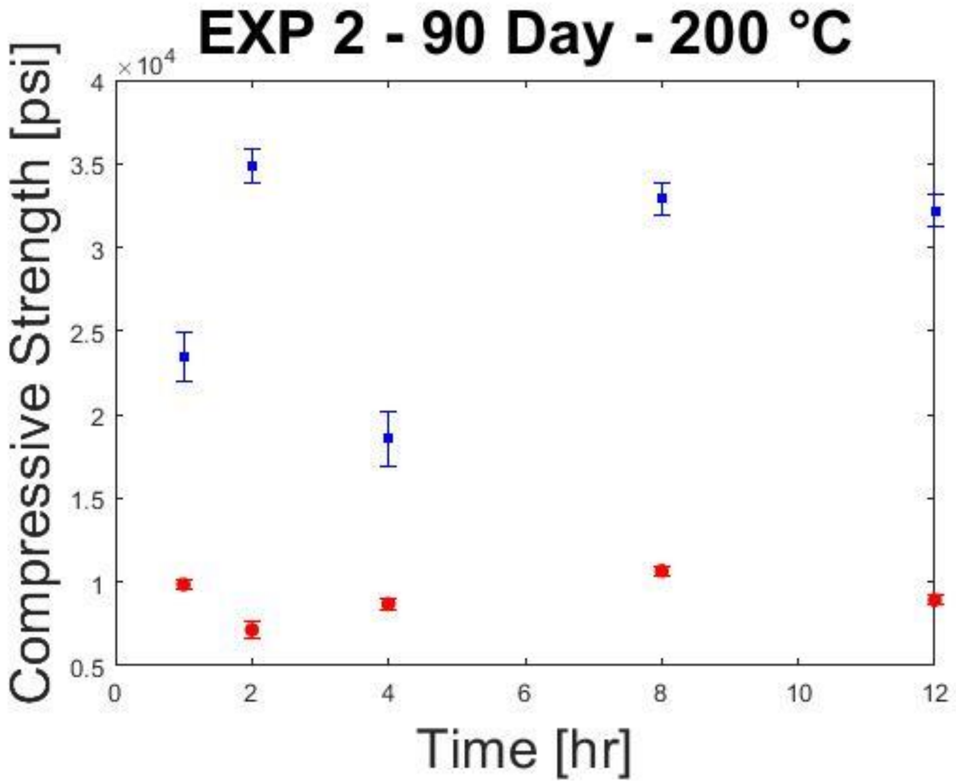

EXP 2 - 28 Day - 225 °C
Compressive Strength [psi]
×10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
Time [hr]

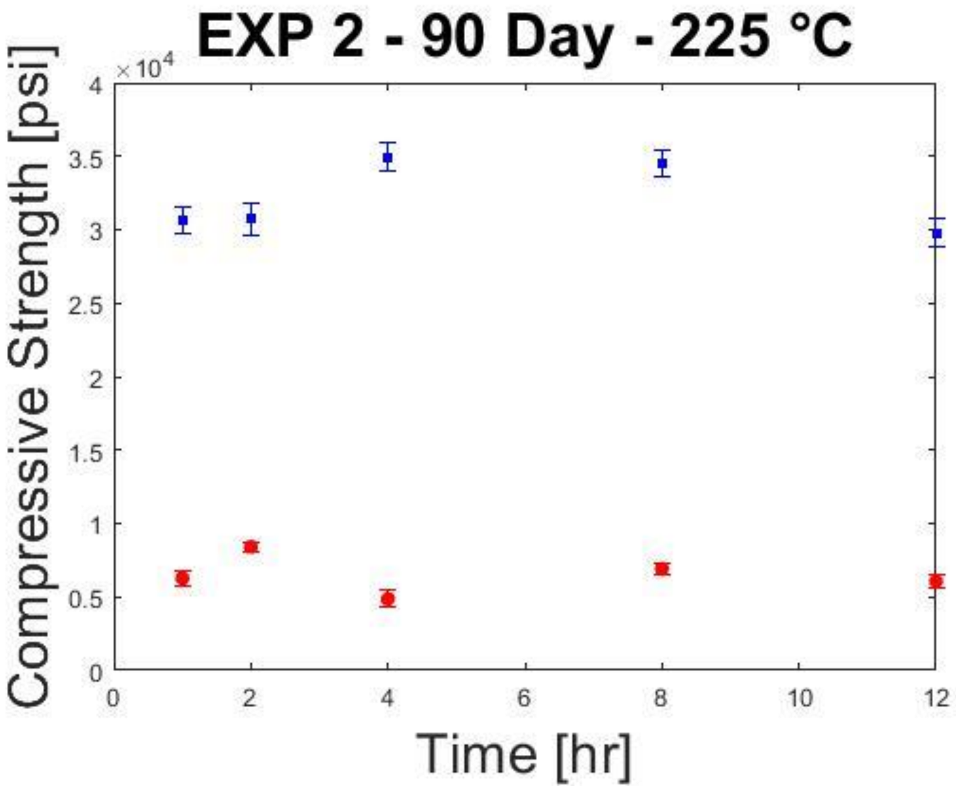

EXP 2 - 90 Day - 100 °C
×10^4
3.5
3
2.5
2
1.5
1
0.5
Compressive Strength [psi]
0
2
4
6
8
10
12
Time [hr]


EXP 2 - 90 Day - 125 °C
×10^4
3.5
3
2.5
2
1.5
1
0.5
Compressive Strength [psi]
0
2
4
6
8
10
12
Time [hr]


EXP 2 - 90 Day - 150 °C
×10^4
Compressive Strength [psi]
Time [hr]
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
8
10
12


EXP 2 - 90 Day - 175 °C
×10^4
Compressive Strength [psi]
Time [hr]
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12


EXP 2 - 90 Day - 200 °C
Compressive Strength [psi]
Time [hr]
×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12


EXP 2 - 90 Day - 225 °C
Compressive Strength [psi]
Time [hr]
×10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12