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TENSILE CAPACITY OF POST-INSTALLED EPOXY-BONDED CONCRETE ANCHORS EXPOSED TO PROLONGED NUCLEAR RADIATION

By

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The members of the committee appointed to examine the thesis of CARYN HAVLOVICK

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THESIS ABSTRACT

Tensile Capacity of Post-Installed Concrete Anchors Exposed to Prolonged Nuclear Radiation

Idaho State University (2017)

With the expansion of the nuclear energy sector growing in the United States, more nuclear facilities are being built and many existing facilities require upgrading to meet current design codes; especially those for seismic loading. As safety is one of the highest priorities in these facilities, the reliability of the structure is key. As upgrades are made to existing facilities, the old structures are taken out and need to be replaced by new ones. The connections using anchor bolts that can no longer be cast into the newly poured concrete are replaced with anchor bolts that are bonded to the existing concrete using epoxy. The purpose of this study is to examine how high amounts of radiation affect the pullout strength of these epoxy-bonded anchor connections.

According to the existing literature, no studies have been done on the effects of radiation on the epoxy-bonded anchors in concrete. However, studies have been conducted on the effects of radiation on each component. Overall, each component's strength seems to decrease with increased exposure to radiation. These results are due to the fact that concrete loses water due to evaporation and dehydration, steel loses toughness, and epoxy loses strength in its chemical bonds and shows signs of micro-cracking. It is expected that the combination of the three components will result in similar findings.

Using twenty normal weight 6” x 12” concrete specimens with a water to cement ratio of 46%, steel anchor bolts with the dimensions of ½” x 4 ½”, and Hilti® HIT HY-100 epoxy, the pullout strength of ten irradiated specimens are found and compared to those of ten control specimens. The irradiated specimens are exposed to 2 x 10^7 rads of gamma radiation at a controlled temperature of 100°C. The specimens undergo pullout testing using a Tinius Olsen machine and a steel box to encase and apply a uniform pressure to the top of the specimens in the direction opposite that of the machine. According to Hilti, the published pullout strength value for 6,000 psi concrete, an anchor bolt with a ½-inch diameter, and an embedment depth of 4 ½ inches, is 7,480 pounds. After the pullout test is completed, compression testing is performed using a Gilson compression machine once the cylinders are cut into 2” x 2” cubes.

The results of the pullout test show the average pullout strength of an anchor bolt embedded one inch is +5,034 pounds for the control specimens and +5,005 pounds for the irradiated specimens. The corresponding average compressive strengths of the control and irradiated specimens are +7,410 psi and +6,652 psi, respectively with an expanded uncertainty of +/-173.8824 lbf. The percent difference in the pullout strength is 0.58%, a percent difference in the compressive strength of 10.23%, with the control specimens having the greater strengths. To normalize the results, the pullout strength is divided by the compressive strength. These results show that the irradiated specimens have greater normalized strengths than the control specimens. This is due to the fact that the pullout strengths are similar in magnitude, but the irradiated specimens' compressive strengths are significantly lower, resulting in greater normalized values. Overall, it is seen that exposure to radiation results in weakening the strengths of materials such as concrete, steel and epoxy. However a 0.58% difference is not significant enough to deter the use of these anchors in nuclear settings.

CHAPTER 1 – INTRODUCTION

1.0 Introduction

Within the nuclear energy industry and associated U.S. Department of Energy research laboratories exist numerous facilities where structural building components are exposed to prolonged radiation during the operation of the facilities. Within this context, steel anchor bolts cast into reinforced Portland Cement Concrete (PCC) are often utilized to anchor pumps, piping, and other mechanical equipment. As upgrades to these facilities occur, it often becomes necessary to utilize post-installed anchor bolts to secure new equipment and piping. These post-installed anchor bolts are installed by drilling into the existing PCC and using an epoxy material to set the steel anchor in place. Once in place, it is very likely that these post-installed anchor bolts will be exposed to nuclear radiation over a prolonged period of time. It is quite possible that over time, this prolonged exposure could lead to degradation of the epoxy which results in diminished structural capacity of the anchor. Failure of an anchor bolt within a nuclear facility could prove catastrophic as these facilities rely on mechanical equipment for proper operation. While the study of the behavior of both PCC and cast in place anchor bolts under nuclear radiation exposure have been carried out, an extensive study on the performance of the post-installed, epoxy set anchors has yet to be undertaken. This poses the question of how does prolonged, high intensity radiation affect the material properties and strength of epoxy-bonded anchors embedded in concrete?

CHAPTER 1 – INTRODUCTION

The purpose of this study is to determine whether or not degradation and loss of tensile strength occurs in post-installed anchors exposed to gamma radiation. The tensile capacity of post-installed anchors exposed to prolonged gamma radiation is determined by constructing PCC specimens, allowing them to cure, and then installing a single, commercially available, anchor. A control batch is then set aside to determine the non-radiation exposure tensile capacity. Additional sample batches are then exposed to 2×10^7 rads of gamma radiation at the Idaho Accelerator Center. After exposure, the samples are tested to determine their relative tensile capacities. The control and irradiated samples are then compared to determine any decrease in tensile capacities. The samples are also visually evaluated for any degradation of the epoxy.

It is noted that the purpose of this study is to develop a framework for the tensile testing of post-installed anchor bolts that are exposed to prolonged nuclear radiation and not present a broad study of the overall performance of these anchors. Within the construction industry there are a number of suppliers of these types of anchors each with their own proprietary anchor types and epoxies. It is the intention of this study to provide proof of concept/ability of this type of testing to manufacturers and suppliers of these type of anchors for the purpose of certifying their use in nuclear facilities. The research presented in this study is significant because while the capacity of both epoxy-bonded and mechanically post-installed concrete anchors (Cook, 1993; McVay, et al., 1996; Cook & Konz, 2001; Gesoglu, 2005; Rolf, et al., 2006) and the effects of ultra-violet radiation on the degradation of epoxies (Kumar, et al., 2002; Liau & Tseng, 1998; Woo,

2007) have been carried out in the past, there is only one study present in the available literature that considers the post gamma radiation capacity of epoxy-bonded concrete anchors (Cook, 1997). This study, carried out at the University of Florida almost twenty years ago, is performed on a single anchor type, using an outdated method of radiation exposure, and only two samples are tested. Furthermore, the developments of new epoxies for these anchors is advancing dramatically, especially in the last twenty years. This study presents a framework whereby currently available epoxy systems are exposed to prolonged gamma radiation and their residual tensile capacities determined. Once a batch of sample anchors are successfully tested, work with manufacturers and suppliers can be done to certify their specific anchors and epoxies for use in nuclear facilities.

1.1 Background

Within nuclear power and research facilities, steel bolts are commonly used to anchor machinery, pumps, and piping to the reinforced PCC superstructure. Some typical types of cast-in-place concrete anchors are shown in Figure 1 (Williams, 2011). The machinery

Figure 1: Typical Cast in Place Concrete Anchors (Williams, 2011)

and piping serve as critical mechanical components to the operation and performance of nuclear reactors.

In several cases, modifications and updates to the original facility require the installation of new machinery and piping. When these updates occur, post-installed concrete anchors are not allowed to be used to secure these components to the existing PCC superstructure according to the current ACI code. As of right now, only cast in place anchors are acceptable. Unlike cast in place concrete anchors whose tensile capacities depends on the bond between the PCC and the anchor, most post-installed anchors rely on the bond between the epoxy and the anchor as well as the bond between the epoxy and the PCC. An example of a typical post-installed concrete anchor is shown in Figure 2 (Williams,

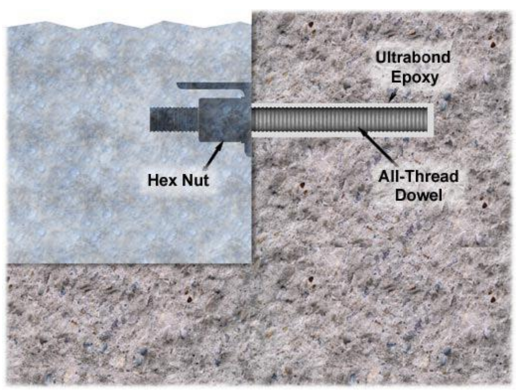

Figure 2: Typical Post-Installed Concrete Anchor (Williams, 2011)

Ultrabond Epoxy Concrete Anchor Systems, 2011).

Because the bond between the epoxy and the anchor/PCC controls the tensile capacity of the anchor, any degradation to the epoxy due to prolonged radiation exposure has the potential to dramatically reduce the anchors' tensile pullout capacity. Due to the fact that in nuclear facilities, failure of most components is deemed to be unacceptable, understanding the reliability of these anchors over time is imperative. This study is seeking to develop a testing methodology whereby the reliability of post installed epoxy anchors exposed to prolonged gamma radiation is determined.

1.2 Objectives and Significance

The objectives of this study are to:

1) Develop a testing methodology and required equipment to determine the reliability of post-installed concrete anchors exposed to nuclear gamma radiation.
2) Provide proof of capability of the testing methodology by carrying out a single round of experiments on a commercially available post-installation epoxy concrete anchor.
3) Determine the degradation and residual tensile capacity of a commercially available post-installation concrete epoxy anchor exposed to 2×10^7 rads of gamma radiation.

Once these three objectives are studied, the results can be used to attract additional research from post-installation anchor manufacturers who wish to have their products certified for use in nuclear facilities.

CHAPTER 2 – LITERATURE REVIEW

2.0 Introduction

This section contains the review of literature concerning irradiated epoxy-bonded anchors in concrete and its effect on the pullout strength. The epoxy and anchors are installed according to the Hilti guides, and the corresponding strengths of each component based on the concrete strength and embedded depth of the anchor are used to determine the non-irradiated industry published pullout strength (Hilti I. , 2014). Since this is a relatively new topic, there does not as yet exist much pertinent literature. As such, the literature review consists of studies that research the effects of radiation on the individual components of concrete, steel, and epoxy. Each of these components and the corresponding studies are summarized in the following sections, followed by the conclusion summarizing the studies and their significance to the topic at hand.

2.1 Concrete

Concrete is the component that houses the epoxy and anchor. Thus, it is an important part of the study since it is the material that needs to be able to withstand the pullout strength of the anchor and epoxy while remaining intact.

2.1.1 Concrete: Optimal Interface

In a study completed by Saleem and others, an analytical model is used to find the optimal concrete interface to decrease the pull-out displacement of anchors bonded to the concrete using two infill/epoxy layers between the anchor and the concrete. (Saleem, et al., 2012).

By modeling the load-displacement curve, shear stress distribution, de-bonded length and the damage of the surrounding concrete, an optimal combination is found to reduce the pull-out displacement. It is found that the elastic modulus of the second infill interface needs to be larger than that of the first infill interface in order to reduce the pull-out displacement, and that the shear strength of the second infill interface also needs to be larger than the first infill interface in order to increase the pull-out load. However, if the shear strength of the second interface is too large, there is more damage done to the concrete, which reduces the bond strength. Although this study is only specific to one part of the current research problem, it is still a valuable source. This study allows one to be able to find the optimum de-bonded length and the shear strength needed for the concrete interface in order to preserve the interface with little to no damage.

2.1.2 Concrete: Neutron and Gamma Radiation

In a study done by Pomaro, a summary of the most distinguished contributions to the topic of radiation damage in concrete from the past 50 years is given (Pomaro, 2016). Most of the studies only model the short-term effects and do not consider the long-term effects. Both neutron and gamma radiation exposure on concrete are discussed. Overall, it is found that the cementitious material within the mix undergoes loss of water, which causes the concrete to shrink and crack/fracture more easily which directly correlates to a decrease in the long-term strength of concrete. The radiation also causes the aggregates within the concrete mix to expand. This is caused by defects in their crystal structures from neutron collisions. The combination of shrinkage of the concrete and expansion of the aggregate leads to a further decrease in the concrete mix's strength. This study is very helpful to the research problem since it discusses the effects of radiation on the components of a concrete's mix. This allows one to understand the effects of radiation on concrete test specimens if it is found that the concrete strength is decreased after exposure to gamma radiation.

Another study by Pomaro and others, analyzes the effect of neutron radiation damage on concrete and how it affects the strength properties of concrete (Pomaro, et al., 2011). The study uses neutron radiation to study the long-term effects on several different concrete mixes. The experimental evidence suggests a decrease/decay of the modulus of concrete, which is connected to the strength of the concrete. This study is relevant in that it deals with effect of radiation on concrete, and how the mechanical properties are affected over a long-term exposure. Although this study uses neutron radiation instead of gamma radiation, the results are a good indicator of what is expected in the current research problem.

2.1.3 Concrete: Maximum Temperature

One of the effects of radiation exposure is an increase in temperature. In order to make sure each component maintains its initial properties and structures, a maximum temperature is determined. Since concrete is more sensitive to temperature due to evaporation and dehydration than the other two components, the maximum temperature for concrete is the control. According to a review done by the Oakridge National Laboratory, the temperature in which evaporation in the concrete accelerates at a faster rate is 100°C, and from 120°C to about 500°C the expulsion of water found in the smaller pores, or chemically combined, starts. Dehydration of the cement paste occurs in the range of 30-300°C with the maximum rate at 180°C (Naus, 2005).

2.2 Steel

The anchor bolts used in the current research are made of steel, so the understanding of the effects of radiation on steel are very important. There is only one relevant study that covers this topic carried out by Margolin and others (2016). The study is concerned with the effect of radiation on the properties of austenitic (steel, nickel, titanium, and chromium mix) steels under static and cyclic loading conditions. It is found that there are large decreases in fracture toughness while swelling increases, but an increase in toughness with lower temperatures (Margolin, et al., 2016). This study shows that the properties of steel, undergo a decrease in toughness and overall strength as it is exposed to radiation at normal temperatures. This study deviates from the current research problem in the fact that it deals with austenitic steel, not regular or high-strength steel anchor bolts. Also, only the fracture toughness in relation to swelling and temperature is measured, and the properties of interest in the current study are the steel and epoxy's tensile strengths. However, this study provides a useful reference to the general effects of radiation on steel materials and as a comparison of results.

2.3 Epoxy

The last component in the current study is the epoxy. There are a limited number of studies done in regard to the effects of radiation on epoxies. Many of them also include the effects of radiation combined with either temperature, condensation, or some other environmental condition.

2.3.1 Epoxy: Radiation and Condensation

The first relevant study is performed by Kumar and others, and it focuses on the effect of ultraviolet radiation and/or condensation on the mechanical properties of reinforced epoxy specimens (Kumar, et al., 2002). After approximately 1000 hours of exposure to ultraviolet radiation, cracking and erosion of the epoxy takes place, resulting in a reduction of the mechanical properties. If the epoxy is exposed to both condensation and ultraviolet radiation, the epoxy's transverse tensile strength is reduced by 29%. If prolonged exposure to ultraviolet radiation and condensation (greater than 1000 hours) is to take place, a structural failure is imminent. While this study focuses on the degradation of epoxy due to ultraviolet radiation and condensation, the effects of gamma radiation on the epoxy is not included. Since there is limited research about gamma irradiated epoxy and resulting effects, this study provides useful procedures that can be referenced and results in which to compare trends. One point of difference in the procedure is that the study exposed the epoxy in cycles over the testing period whereas the current study exposes the epoxy (along with the concrete and bonded anchors) continuously with a higher intensity of gamma radiation for the testing period. Another difference is that the effects of condensation are accounted for, whereas the current study is only concerned with the effects of radiation.

2.3.2 Epoxy: Radiation and Temperature

Another similar study is performed by Humer and others. This study investigates the effect of radiation at extreme temperatures (77K for property testing and ~340K for irradiation testing) on new epoxy based glass fiber reinforced plastics (GFRPs) and cyanate ester (CE) matrix systems. The testing procedures are carried out in accordance with the American Standard for Testing Materials (ASTM) methods. The mechanical properties of tension and shear are tested using static and dynamic loading and analyzed before and after the epoxy is irradiated.

The results show that the new epoxy based GFRPs display decreased mechanical properties after radiation, but the other blends show either no change or an increase in the mechanical properties (Humer, et al., 2006). As a result, the study suggests adding extra insulation to the systems that use the new epoxies in order to protect from degradation. The study suggests further research in the areas of cyclic loading and extended exposure. Similarly, a study done by Park and many others also examines the combined effect of temperature and radiation (Park, et al., 2004). This study is significant to the current research problem in the fact that it deals with irradiated epoxies. This study focuses on the thermal properties of radiation on epoxy-coated systems on steel. Two epoxy systems are used and irradiated at different dose rates. Overall, it is seen that the radiation reduces the internal thermal stability and hardening of the epoxy systems.

These two studies deviate from the current research problem in that they test and irradiate the epoxies at extreme temperatures, whereas the current research specimens are exposed at a constant controlled temperature of 100°C. Another deviation is that Humer's study only focuses on chemical composition of epoxies and different mixes, and how well each epoxy handles irradiation. In the current study only one epoxy mix is tested, and only the effects of radiation on the epoxy, anchor bolt and concrete cylinder are evaluated. However, both studies provide good insight on the effects of radiation on certain epoxy mixtures, and which epoxies are more durable after being irradiated at certain temperatures.

Another study performed by Milkovich and others investigates the effects of radiation at differing temperatures of gamma radiation with an intensity of 1.0 MeV and a total dose of 1.0 x 10^{10} rads on graphite epoxy (Milkovich, et al., 1985). The intensity and dose are approximately equal to what the epoxy is exposed to if it is in space for 30 years. At temperatures ranging from – 250°F to +250°F, the mechanical properties of the epoxy are analyzed. It is found that the temperature changes the material properties and influences the rate at which the epoxy experiences degradation. Overall, it is found that exposure to gamma radiation decreases the shear and tensile strength of the epoxy by degradation of the matrix chemistry within the epoxy.

The Milkovich study is useful to the current research topic in the sense that it investigates the effects of gamma radiation on epoxy. However, this study focuses mainly on the combined effects of radiation and temperature due to the fact that an environment similar to space needs to be replicated. Within the current research topic, the effects of wide ranges of temperatures on the mechanical properties of epoxy are not a concern since the temperature is held constant at 100°C. Also, the epoxy is the only variable tested within this study compared to the epoxy-bonded anchors installed in concrete cylinders that are tested. The overall effects of radiation to the epoxy may or may not be the same since it is encased in concrete. With this in mind, the study's results and analysis provide a good reference and comparison for the current research topic.

2.3.3 Epoxy: Radiation and Annealing

In a study done by Sekulic and Stevanovic, gamma radiation and an annealing process are used and the micro-hardness of the tested materials are analyzed. The materials are irradiated at various doses and then thermal treatments are applied at 180°C and 250°C in a vacuum. A control is used to compare the results. This technique is known as the nanoindentation technique, and it finds the hardness and Young's modulus of the carbon/epoxy composites. It is found that as radiation exposure increase, the properties of the composites decrease (Sekulic & Stevanovic, 2011).

This research study is applicable to the current research problem because it deals with the effects of gamma radiation on carbon/epoxy composites. However, it also deals with an additional annealing process, not included in the present research.

2.4 Conclusion

Even though no study exists that exactly replicates or considers the same variables as the current study, there are studies performed that dealt with each component individually. For concrete, it is determined that an optimal interface is desired, and that radiation can cause a decrease in strength by water evaporation which then causes shrinkage to occur (Saleem, et al., 2012; Pomaro, 2016; Pomaro, et al., 2011). In regard to steel, only one relevant study is found that discusses the effects of radiation on metal alloys. The study finds that at normal temperatures, the hardness and strength of the steel decrease (Margolin, et al., 2016). The studies dealing with epoxy vary in application such as radiation and condensation, radiation and temperature, radiation and annealing, and radiation with different types of epoxies. Overall it is found that the epoxies degraded after being irradiated and that their strength decrease due to internal chemical damage or micro-cracking (Humer, et al., 2006; Kumar, et al., 2002; Milkovich, et al., 1985; Park, et al., 2004; Sekulic & Stevanovic, 2011). Through all these studies, it is shown that radiation negatively affects the mechanical properties and strength of concrete, steel and epoxy.

CHAPTER 3 – METHODOLOGY

3.0 Introduction

The relative effect of gamma radiation on the tensile pullout capacity of post-installed epoxied anchors is investigated in accordance with Section 7.10 of the Standard Test Methods for Testing Bond Performance of Bonded Anchors, ASTM E1512-01 (ASTM, 2015). Ten irradiated specimens are compared to ten control specimens. The casting and testing of the cylinders takes place in the Lillibridge Engineering Building's Civil Engineering Materials Laboratory (CEMTL) in accordance to the Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM C192/C192M-15 (ASTM, 2015). The cylinders selected to be exposed to gamma radiation are sent to the Idaho Accelerator Center (IAC) and are exposed to 2 x 10^7 rads of gamma radiation according to the Standard Test Methods for Testing Bond Performance of Adhesive-Bonded Anchors, ASTM E1512-97 (ASTM, 1993). The compressive strength of the specimens are tested in accordance to the Standard Test Method of Compressive Strength of Cylindrical Concrete Specimens, ASTM C39/C39M-05 (ASTM, 2015) and the Standard Test Method of Compressive Strength of Hydraulic Cement Mortars, ASTM C109/109M-07 (ASTM, 2016). This section discusses the methods and procedures that are used in this research study.

3.1 Facilities and Resources

Three facilities are utilized to carry out the objectives of this study and they are the CEMTL and the IAC located in Pocatello, ID, and the Technology Building Laboratory located in Logan, UT. The creation of specimens, installation of anchors and epoxy, and tensile and compression testing are carried out at the CEMTL, the radiation exposure is carried out at the IAC, and the formation of the compression testing specimens is carried out at the Technology Building Laboratory. It is noted that all radiation protocols for handling of the irradiated specimens are administered by the trained staff of the IAC.

One piece of testing equipment, a Portland Cement Concrete (PCC) steel box, is fabricated for this study, and can be used for future studies of post-installed epoxy anchor as funded by anchor manufacturers.

3.2 Mix Design

Before the casting and testing of specimens occurs, an adequate concrete mix is found in accordance with ASTM C192/C192M-15 (ASTM, 2015). Using a laboratory mix design used for Idaho State University's (ISU's) Civil Engineering Materials Lab, an initial test mix design is made and tested. An additional 4% increase in the water to cement (w/c) ratio is applied in order to increase the workability of the mix and decrease the overall compressive strength. The initial test mix design is composed of the components shown in Table 1.

Table 1. Mix Design

	1 ft³		4" x 8" Cylinder			
	Volume (ft^3)	**Weight (lbs.)**	**Volume (ft^3)**	**Weight (lbs.)**	**Total Weight (5 cylinders)**	**Total Weight (+30%)**
Air	0.0552	0.0000	0.00321	0.0000	0.0000	0.0000
Water	0.1722	11.7734	0.0100	0.6485	3.4247	4.4522
Cement	0.1041	20.4568	0.0061	1.1901	5.9506	7.7358
Fly Ash	0.0352	5.1376	0.0020	0.2989	1.4945	1.9428
Coarse Aggregate	0.3926	64.6741	0.0228	3.7626	18.8129	24.4568
Fine Aggregate	0.2407	39.3582	0.0140	2.2898	11.4488	14.8835
Total	1.0000	140.3734	0.0582	8.1666	40.8330	53.0829

The mix design uses a base of 1 ft^3 of concrete in order to calculate the weight of each component needed for five 4" x 8" cylinders. The calculations used within the spreadsheet consist of a volume and weight calculation. The volume of the 4"x 8" cylinders is calculated using Equation (1).

$$\forall_{4x8} = \frac{\pi d^2}{4} \times h = \frac{\pi (4\ in)^2}{4} \times 8\ in \times \left(\frac{1\ ft^3}{1728\ in^3}\right) = 0.0582\ ft^3 \qquad (1)$$

Where: $\forall_{4x8}$ = the 4" x 8" cylinder volume (ft^3)

d = the cylinder's diameter (in)

h = the cylinder's height (in)

The components' volume of the 4" x 8" cylinders are found by multiplying the 1 ft^3 volume of the component by the total volume calculated. The weight of each component is found using a volume to weight converter. (Cubic Foot to Pounds Converter, 2016). The water to cement ratio is calculated by dividing the weight of the water by the sum of the cement and fly ash weights and is shown in Equation (2).

$$\frac{w}{c}\, ratio = \frac{water}{cement + fly\ ash} \times 100 = \frac{11.7734\, lbs}{20.4568\, lbs + 5.1376\, lbs} \times 100$$
$$= 46\ \% \qquad (2)$$

The initial mix design cast a total of five 4” x 8” specimens. Two of the specimens are removed from the bath after 14 days, capped and tested for their compressive strength in order to make sure the 14-day strength does not exceed the limit of 5,000 psi. If the specimens’ strengths are below 5,000 psi, then the other three specimens are tested for the 28-day strength. However, if the 14-day strength exceeds 5,000 psi then the mix design fails its criteria and a new mix design is made. The concrete specimens need to have a compressive strength less than 5,000 psi in order to make sure the anchor bolts pull cleanly out of the concrete. It is found that this mix design meets the requirements, and is therefore used to cast the test specimens.

3.3 Timeline

The following timeline is followed for both the control batch and the irradiated batch of specimens to ensure the casting, curing, installation, and testing happen within the same time intervals as shown in Table 2.

Table 2. Timeline

Action	Days
Cast Concrete Cylinders	1
Cure in Water	1-28
Wait Time	29-60
Embed Anchors	60
Cure	60-74
Wait Time	74-77
Arrived, Tested and Removed from IAC	77-84
Wait Time	84-98
Pullout Test	98
Wait Time	98-103
Compression Test	103

During the wait time, the specimens sit in the laboratory at room temperature.

3.4 Casting and Curing of Specimens

Once the mix design is set, a total of twenty-two test specimens are cast in accordance to ASTM C192/C192M-15 (ASTM, 2015). Two batches are made at different times. The first batch consists of 12 specimens, and the second batch consists of 10 specimens. There is no random selection of the specimens. Ten of the specimens are used as a control, two are extras in case of mishap during the anchor bolt installation process, and the other ten are sent to the IAC to be exposed to radiation. All specimens are removed from their plastic molds 24 hours after being cast. After removal, the cylinders finish curing in a water bath for 28 days according to ASTM C192/C192M-15 (ASTM, 2015).

3.5 Imbedding Anchor Bolts

After the test specimens are cured for twenty-eight days, a Hilti® HIT HY-100 epoxy with a HIT-V ½”-diameter by 4 ½”-length anchor is installed in each sample according to the manufacturer’s specifications (Hilti, 2014). The 4 ½ inch anchor bolt used is shown below in Figure 3.

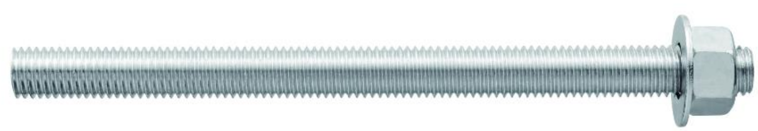

Figure 3. Hilti Anchor Bolt (Hilti, 2014)

The concrete cylinders are placed back into the plastic molds, which provide containment during the installation of the anchor bolts. One-inch deep holes for the anchors are drilled using a 5/8” carbide tipped concrete bit. The inside surface of each drilled hole is cleaned in accordance with the manufacturer’s instructions using compressed air and a nylon bristle brush (Hilti, 2014). The final result after the drilling is complete is shown in Figure 4.

Figure 4. Concrete Specimens after Hole for Anchor Bolt is Drilled

The epoxy is then applied according to the manufacturer's instructions (Hilti, 2014). Once anchor bolts are imbedded and the epoxy applied, the samples are allowed to cure for a minimum of fourteen days. Figure 5 shows one batch of the final specimens with the anchor embedded and the epoxy cured.

Figure 5. Concrete Specimen after Anchor and Epoxy are Embedded

3.6 Construction of PCC Box

While the epoxy is curing, a piece of equipment to facilitate testing is constructed. This piece of equipment is a steel box that is placed around each cylinder during the tensile testing in order to control premature cracking of the concrete base materials. The steel box is larger in diameter and slightly taller than the concrete specimens, with a slotted area on the top of the box to allow room for the anchor bolt to be attached to the testing machine. A large circular plate, similar in design to a washer, with the same diameter as the specimens is used to apply the same pressure over the top surface of the specimen so that the slotted area does not cause uneven pressure distributions and premature cracking of the concrete. The ½”-diameter anchor’s adhesive design strength, in concrete of $f'_c = 6{,}000$ psi, is 7,840 lbs. for an effective embedment depth of 4 ½ inches (Hilti, 2014). Therefore, the PCC steel box and connections have strengths greater that 7,840 lbs. so that the anchor pulls completely out of the concrete with no failure of the PCC steel box. The box is connected to a large steel plate with a steel extension at the bottom that attaches to the testing machine via grips as shown in Figure 6.

Figure 6. PCC Steel Box

3.7 Specimen Exposure to Gamma Radiation

After the epoxy curing is complete, ten samples are delivered to the IAC and are individually exposed to at least 2 x 10^7 rads of gamma radiation over the top surface of the specimen at the epoxy-anchor-concrete connections (ASTM, 1993). A rad is defined as a unit of absorbed radiation dose of 100 ergs of energy per one gram of matter. An accelerator is used to generate the electrons used to radiate the testing specimens. The calculated penetration depth for the epoxy-anchor-concrete specimens is ≈1.0 inch based on the density of each component. The set-up at the IAC used for testing is shown in Figure 7.

Figure 7. IAC Testing Set-up

The control station that the IAC operator uses to start and stop the test, watch the specimens, and monitor the accelerator readings is shown below in Figure 8.

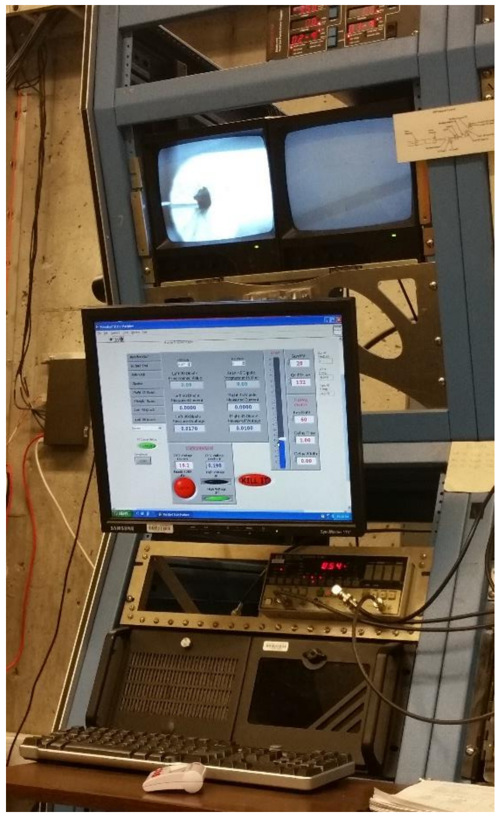

Figure 8. IAC Control Station

The readout for the number of pulses being received by each specimen is separate from the control station and is shown in Figure 9.

Figure 9. Pulse Readout

To apply a consistent dosage across the entire surface of the test specimens, the cylinders are rotated 90° when the pulses reach the quarter, half, and three-quarter marks of the final pulses.

The temperature is maintained to a maximum of 100°C (Naus, 2005), and the readout for the temperature at the surface of the test specimens is determined by a thermocouple and the data is transferred to a laptop as shown in Figure 10.

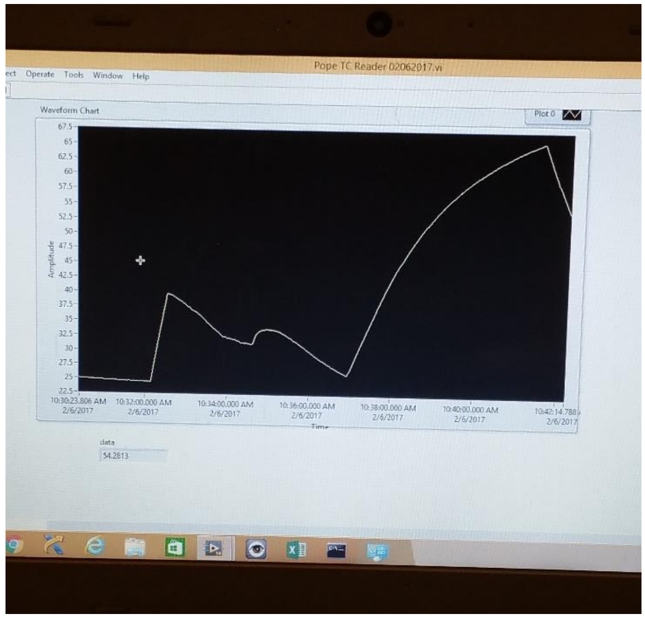

Figure 10. Temperature Readout

After exposure, the samples sit in a containment vault at the IAC to allow for decontamination of the specimens.

To verify that the testing specimens (comprised of the anchor bolt, epoxy, and concrete cylinder) do not become radioactively contaminated, each component is exposed prior to the actual testing. This allows the IAC to determine the rate and intensity at which to expose the testing specimens, determine the amount of time and number of pulses required to reach 2×10^7 rads, decide the number of test specimens to be exposed based on the timing and budget, and to make sure the test specimen does not become radioactive.

3.8 Testing of Specimens

Once the radiation levels of the specimens reach acceptable levels, as determined by the staff at the IAC, the samples are transported to the CEMTL. The samples are then tested according to ASTM E 1512-01 using a Tinius Olsen Universal Testing Machine (UTM). During loading, a continuous tensile load is applied using a center-hole hydraulic ram. The load and displacement of each anchor is continuously measured during the testing and an ultimate tensile load at failure is recorded. The measurement of the UTM is unknown. The pullout testing setup with both the steel box and specimen is shown in Figure 11.

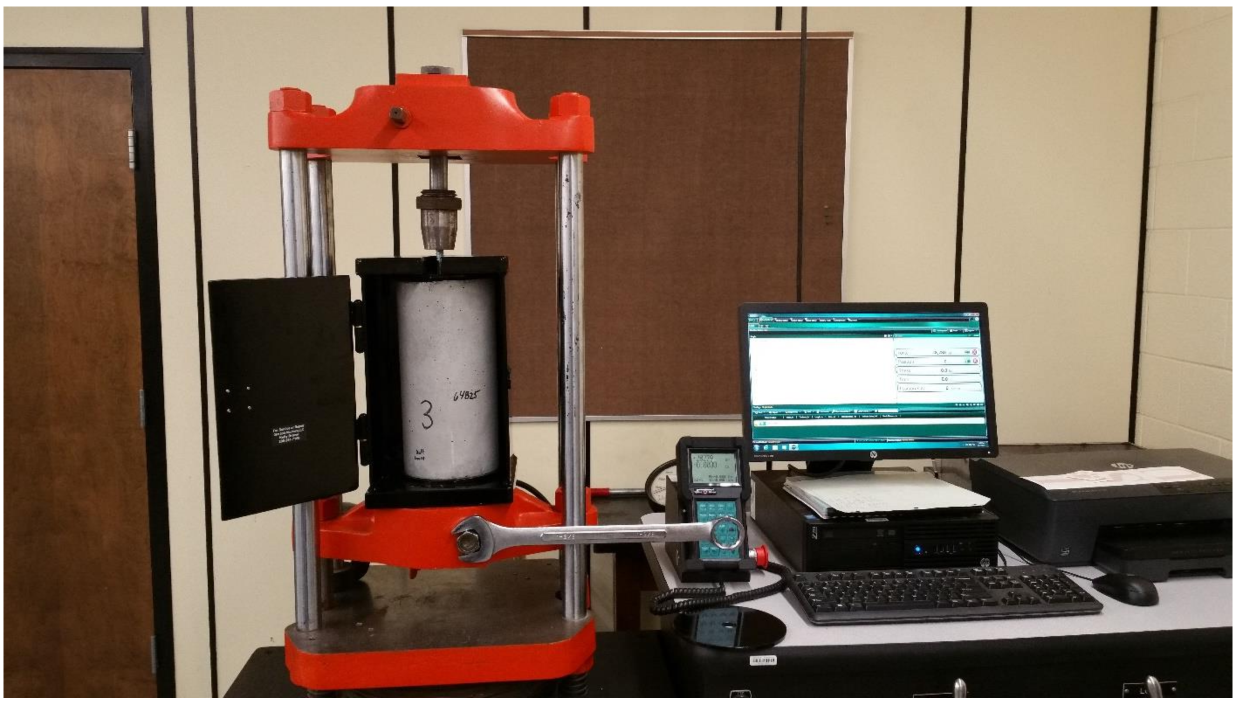

Figure 11. Pullout Testing Setup

Additionally, the failure mode of each specimen is visually evaluated and recorded and is shown in Appendices A and B. The relative strength of the irradiated specimens are then obtained by comparing them to the control samples.

CHAPTER 3 – METHODOLOGY

The compressive strength of the cylinders are determined after 2” x 2” cubes are cut out of the 6” x 12” cylinders. This procedure was accomplished at the Utah State University Technology Building Laboratory in Logan, UT using a wet saw as shown in Figure 12.

Figure 12. Set-up for Cutting Concrete Cubes

The cubes are cut out of the base of the cylinders because the top of the cylinder underwent stress during the tensile testing, which results in inaccurate values for the compressive strength. Figure 13 displays the finished results after cutting the specimens into cubes.

Figure 13. Final Product of Cubes from Cylinders

Five days after the pullout test, the cylinders are cut and compression tested in the Gilson Compression machine according to ASTM C39/C39M-15a (ASTM, 2015) as shown in Figure14.

Figure 14. Setup for Compression Testing of Cubes

The measurement uncertainty for the Gilson Compression machine is +/-173.8824 lbf for a loading range of 30,000-285,000 pounds. The specimens are visually inspected and pictures are taken before and after the compression test. These pictures are found in Appendices C and D.

3.9 Safety Procedures

During the mixing, casting, and testing of the specimens, the required safety precautions are followed:

- Workspaces are cleared of all un-needed items
- Safety glasses, work shoes and appropriate clothing are worn at all times
- Gloves are worn to protect hands from chemicals present in the mix design
- Fan is turned on to limit the amount of dust in the room during mixing and installation
- Doors to the compression testing machine are shut at all times during testing
- Dust mask is worn when embedding the anchors in the concrete
- Ear plugs are worn when cutting the cylinders into cubes

When the test specimens are being exposed at the IAC, everyone participating in the testing is required to wear a personal whole-body dosimeter and a pencil dosimeter to monitor the amount of radiation exposure received individually. This precaution is necessary to make sure no one receives doses greater than the required limits set by the university and the state. Once the specimens are irradiated, the Technical Safety Office

(TSO) runs tests to make sure nothing is contaminated. Once the tests come back clean, the specimens are released for further testing, and no additional radiation precautions are taken.

CHAPTER 4 – LABORATORY TESTING RESULTS

4.0 Introduction

This section provides the laboratory results from the performed experiments and tests. Initially, a mix design is cast, cured and tested to make sure the compressive strengths are within the desired limits. Next, the testing specimens are made in two batches due to limited curing space. Once the test specimens are cured, the anchors embedded, and the epoxy cured, one batch is sent to the Idaho Accelerator Center (IAC) to be exposed to radiation and the other is kept at Civil Engineering Materials Testing Laboratory (CEMTL) as a control batch. As soon as the specimens are released from the IAC, they undergo testing to determine the pullout strength. The values are recorded and visual observations are made. Once the pullout strength is determined, the compressive strength is found after cutting the cylinders into 2” x 2” cubes.

4.1 Irradiation Results

Before the batch that is to be irradiated is sent to the IAC, a concrete cylinder, a steel anchor bolt, and a sample of the epoxy is tested at an energy of 12 MeV to observe what happens to each component. At this energy level the concrete cylinder cracked, the steel anchor bolt glowed cherry-red, and the epoxy started smoking due to the high temperatures. It is found that an energy level of 8 MeV is sufficient to reach the desired dosage of gamma radiation while the integrity of each component is maintained. The batch that is sent to the IAC to undergo radiation receive 2 x 10^7 rads of gamma radiation. The operators at IAC use the concrete, anchor and epoxy densities, desired energy level, and the amount of radiation required to calculate the time it takes and pulses needed per specimen to reach the 2 x 10^7 rads of gamma radiation. The target number f pulses calculated is 64,815 with an approximate exposure time of 15 minutes. Table 3 shows the number of pulses each specimen receives at the IAC.

Table 3. Number of Pulses Received

Specimen	Pulses
I-1	64,822
I-2	64,815
I-3	64,825
I-4	64,815
I-5	64,825
I-6	64,819
I-7	64,826
I-8	64,889
I-9	64,816
I-10	64,816

It is expected that the degradation of the epoxy due to exposure to gamma radiation is caused by a change in the chemical makeup of the epoxy. To make sure a significant amount of water is not lost during the radiation treatment, the weight of the cylinders before and after exposure are recorded. The percent difference is calculated as the difference between the initial and final weights divided by the initial weight. These values are shown in Table 4.

Table 4. Initial and Final Irradiated Specimen Weight

Specimen	Initial Weight (lbs.)	Final Weight (lbs.)	Percent Difference (%)
I-1	28.79	28.85	- 0.20 %
I-2	28.66	28.65	0.04 %
I-3	28.44	28.45	- 0.04 %
I-4	28.62	28.60	0.06 %
I-5	28.48	28.50	- 0.06 %
I-6	28.44	28.45	- 0.04 %
I-7	28.75	28.75	- 0.01 %
I-8	28.57	28.55	0.08 %
I-9	28.31	28.30	0.03 %
I-10	28.44	28.45	0.04 %

These results show that no significant amount of water is lost during exposure to radiation.

4.2 Compression Testing Results

The compression testing is comprised of two sections. The first section is the testing of the initial mix design to make sure the mix design fits within the desired specifications. The second section covers the compression testing of the twenty 2” x 2” concrete specimens needed to determine the strength of the ten 6” x 12” concrete specimens that underwent irradiation and the ten specimens used for control. This testing occurs five days after the pull-out testing for both the control and irradiated epoxy-bonded anchor bolts.

4.2.1 Initial Mix Design Compression Testing

Two specimens compressive strengths, tested at 14 days, are 4,821 psi and 2,796 psi with a mean strength of approximately 3,808 psi. Since the average 14-day strength is below the desired 5,000 psi strength, the remaining three specimens are tested at 28 days and are shown in Figure 15.

Figure 15. Mix Design Cylinders

The 28-day strength of the three remaining specimens are in the 4,000 psi to 6,000 psi range which is within the desired limits.

4.2.2 Testing Specimens' Compressive Strength

The compression tests take place after the pullout tests for both the control and irradiated specimens. Once the pullout testing occurs, it takes a total of five days to transport the cylinders to Utah State University in Logan, UT (USU) where they are cut into cubes. They are then brought back to Idaho State University (ISU) to undergo the compression testing. Since the compression testing occurs 103 days after being cast, the 103-day compressive strength is converted to 28-day compressive strength by a conversion factor shown in Equation (3) (Nawy, 2009).

$$conversion\ factor = \frac{t}{4 + 0.85t} \qquad (3)$$

Where: t = the total number of days concrete is cured after being cast

Once the conversion factor is calculated, the 28-day compressive strength is determined using Equation (4).

$$f'_c = \frac{f_{ct}}{conversion\ factor} \qquad (4)$$

Where: f'_c = 28-day compressive strength (psi)

f_{ct} = 103-day compressive strength (psi)

Once the cubes are cut, the dimensions are measured so that the area of each cube is calculated. Table 5 shows the dimensions of width and thickness and the resulting area of the control batch.

Table 5. Control Dimensions and Areas

Specimen	Width (in)	Thickness (in)	Area (in^2)
C-1	2.090	2.100	4.389
C-2	2.147	2.096	4.500
C-3	2.183	2.094	4.571
C-4	2.085	2.088	4.353
C-5	2.061	2.135	4.400
C-6	2.069	2.134	4.415
C-7	2.116	2.075	4.391
C-8	2.074	2.123	4.403
C-9	2.097	2.064	4.328
C-10	2.061	2.026	4.176

The area and dimensions of the irradiated batch are shown in Table 6.

Table 6. Irradiated Dimensions and Areas

Specimen	Width (in)	Thickness (in)	Area (in^2)
I-1	2.026	2.011	4.074
I-2	2.043	2.050	4.188
I-3	1.986	1.970	3.912
I-4	2.038	1.973	4.021
I-5	2.020	2.031	4.103
I-6	2.024	2.018	4.084
I-7	2.003	1.942	3.890
I-8	2.032	2.047	4.160
I-9	2.015	2.016	4.062
I-10	2.024	2.029	4.107

The compressive strength is calculated by dividing the compressive force by the cube's area. Table 7 gives the compressive force and resulting compressive strength of both the 103 day and 28-day strengths of the control specimens.

Table 7. Control Compressive Strength

Specimen	Compressive Force, P_{comp} (lbs.)	Compressive Strength, 103-day (psi)	Compressive Strength, 28-day (psi)
C-1	28,330	6,455	5,737
C-2	32,110	7,135	6,342
C-3	39,760	8,698	7,731
C-4	37,610	8,639	7,679
C-5	42,970	9,765	8,680
C-6	29,740	6,736	5,987
C-7	43,470	9,900	8,800
C-8	32,520	7,386	6,565
C-9	39,460	9,117	8,103
C-10	39,820	9,536	8,476

Table 8 gives the values for the compressive strength of both 103-day and 28-day strengths of the irradiated batch.

Table 8. Irradiated Compressive Strength

Specimen	Compressive Force, P_{comp} (lbs.)	Compressive Strength, 103-day (psi)	Compressive Strength, 28-day (psi)
I-1	24,450	6,001	5,334
I-2	33,190	7,943	7,044
I-3	32,350	8,264	7,349
I-4	27,750	6,901	6,134
I-5	22,300	5,436	4,831
I-6	34,960	8,559	7,608
I-7	28,090	7,221	6,419
I-8	26,350	6,335	5,631
I-9	34,070	8,387	7,455
I-10	33,150	8,072	7,175

Figure 16 shows the plot of the controlled and irradiated specimens’ 28-day compressive strength.

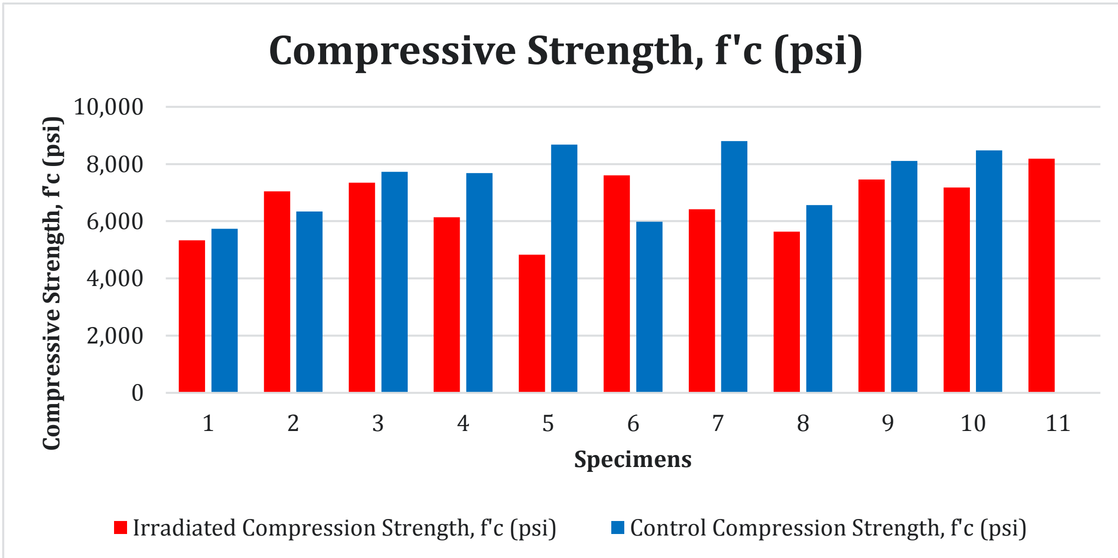

Figure 16. Compressive Strength

Once the specimens undergo compression testing, the final results are recorded. The average compressive strength of control and irradiated specimens are 7,410 psi and 6,652 psi, respectively. The control batch's standard deviation is 1,096 psi and the irradiated batch's standard deviation is 1,011 psi. A graph depicting these values is shown in Figure 17.

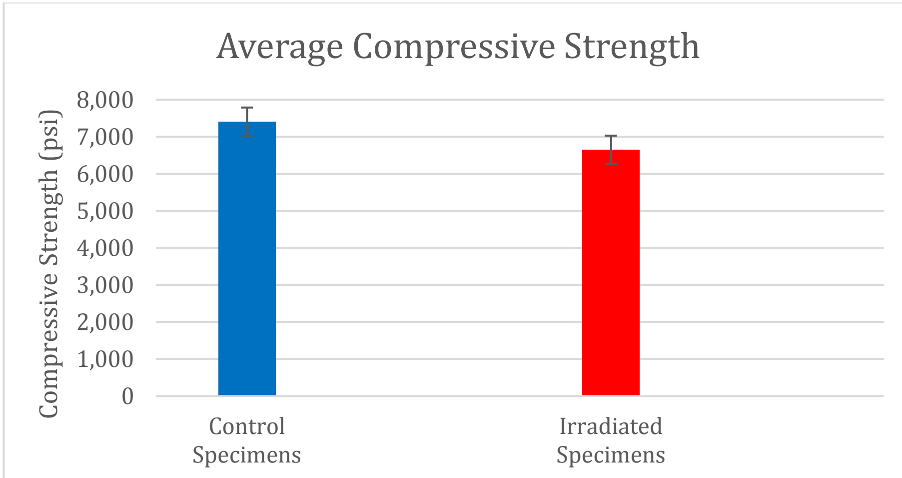

Figure 17. Average Compressive Strength

An error bar showing one standard deviation of each average is included in the graph. Since the standard deviations are very similar, it is concluded that the statistical difference between the control and irradiated specimens' average compressive strength is insignificant. The initial and final failure pictures are shown in Appendices A and B.

4.3 Pullout Testing Results

The pullout strength testing is split into two sections. The first section tests the pullout strength of the control group (specimens not exposed to radiation). Ten 6" x 12" specimens are used for the control set. The second section tests the pullout strength of the remaining ten 6" x 12" irradiated specimens. Since the control batch of specimens is made after the batch of specimens undergoing radiation, the pullout testing occurs using the same amount of time that elapsed after casting each batch.

4.3.1 Control Specimens' Pullout Strength

After a period of 98 days from being cast, the control specimens are tested. Table 9 gives the values for the pullout strength of the control batch.

Table 9. Control Pullout Strength

Specimen	Pullout Strength, P_{out} (lbs.)
C-1	4,496
C-2	5,287
C-3	4,787
C-4	3,147
C-5	6,654
C-6	4,609
C-7	6,305
C-8	5,357
C-9	4,700
C-10	4,995

4.3.2 Irradiated Specimens' Pullout Strength

The irradiated specimens are released from the IAC 84 days after being cast. The pullout testing occurs 14 days later for a total of 98 days between being cast and pullout tested. Table 10 gives the values for the pullout strength of the irradiated batch tested 98 days after being cast and 18 days after being irradiated at IAC.

Table 10. Irradiated Pullout Strength

Specimen	Pullout Strength, P_{out} (lbs.)
I-1	4,650
I-2	5,110
I-3*	4,960
I-4	5,260
I-5	5,490
I-6	6,380
I-7	4,320
I-8	6,230
I-9	3,530
I-10	4,210

* This specimen is observed to have a slightly loose anchor connection

The plot of the control and irradiated specimens' pullout strength is shown below in Figure 18.

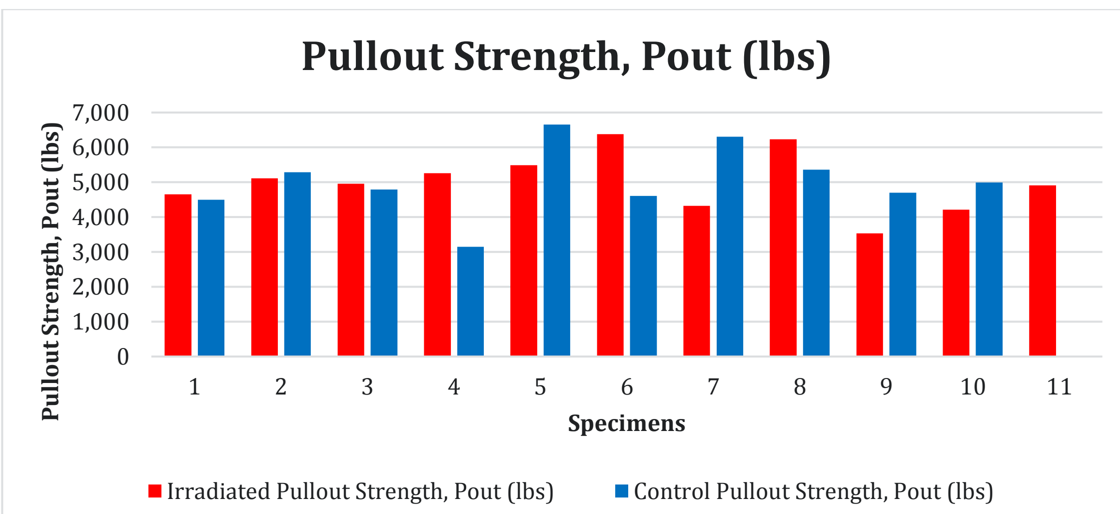

Figure 18. Pullout Strength

The average pullout strength of the control batch is 5,034 pounds with a standard deviation of 928 pounds. The average pullout strength of the irradiated batch is 5,005 pounds with a standard deviation of 804 pounds. A graph of these values is shown in Figure 19.

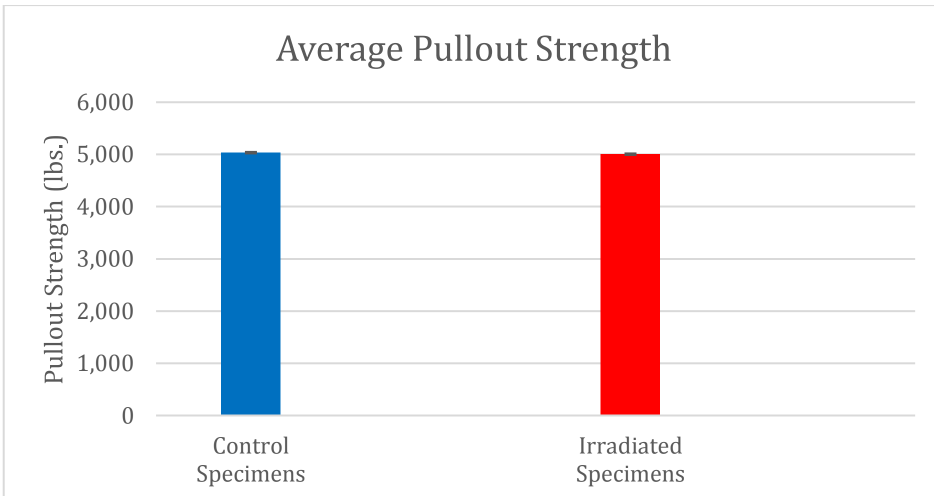

Figure 19. Average Pullout Strength

Error bars indicating one standard deviation of both the control and irradiated specimens are used. Much like the compressive strength, the standard deviations are almost identical such that the statistical difference between them is minimal. A graph giving a closer view of the difference in the pullout strength and the error bars is shown in Figure 20.

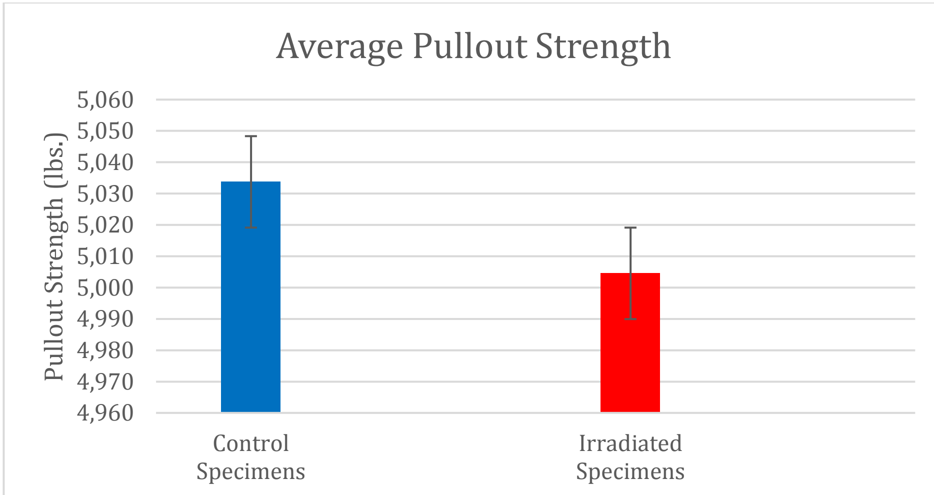

Figure 20. Close-up of the Average Pullout Strength

The standard deviation between the control and irradiated batches pullout strength is 14.06 pounds with a percent difference of 0.58 %. This small of a variation between the control and the irradiated specimens demonstrate that little to no tensile capacity is lost to the post-installed anchor bolts during exposure to radiation.

The specimens of both the control and irradiated batches are visually inspected before and after the testing and recordings of the failure modes are taken. It is seen that the majority of the specimens failed due to delamination between the epoxy and the concrete with little to no surface cracking on the concrete face as shown in Figure 21.

Figure 21. Majority Failure Surface of Specimens

A select few show surface cracking on the face, and it is observed that the concrete surface failure is such that the top portion of the cylinders, up to one inch which is the embedment depth, can be removed as shown in Figure 22.

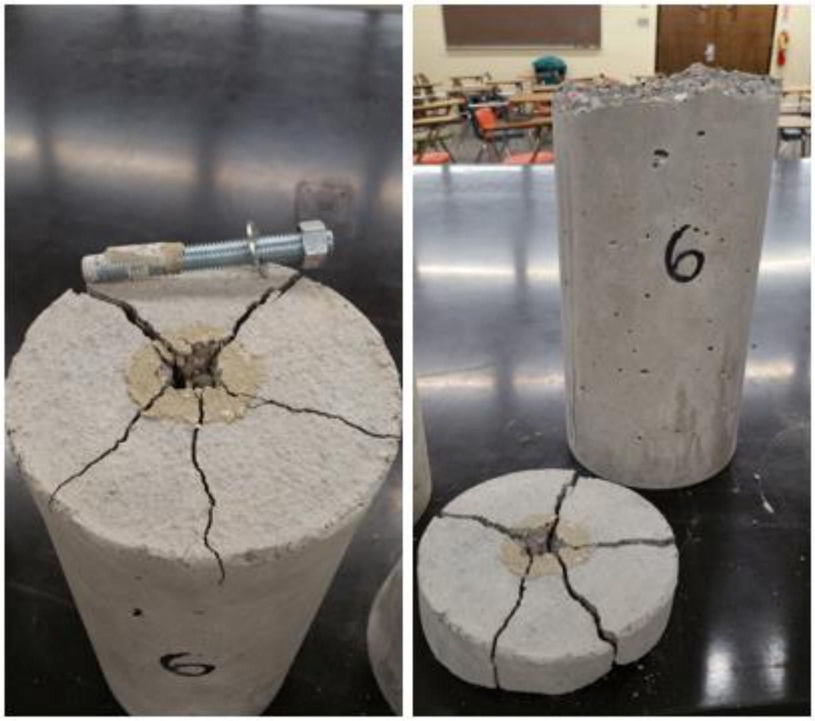

Figure 22. Cracked Failure Surface

The full records of the failure modes are presented in Appendices C and D.

4.3.3 Normalized Pullout Strength

In order to normalize the pullout strength of each specimen for comparison, each specimen's pullout strength is divided by both the compressive force and the compressive strength. This information for the control and irradiated specimens are shown in Table 11.

Table 11. Control Normalized Results

Specimen	Control		Irradiated	
	P_{out} / P_{comp}	P_{out} / f'c (in^2)	P_{out} / P_{comp}	P_{out} / f'c (in^2)
1	0.1587	0.7837	0.1902	0.8718
2	0.1647	0.8337	0.1540	0.7255
3	0.1204	0.6192	0.1533	0.6749
4	0.0837	0.4098	0.1895	0.8575
5	0.1548	0.7666	0.2462	1.1363
6	0.1550	0.7699	0.1825	0.8386
7	0.1450	0.7165	0.1538	0.6730
8	0.1647	0.8161	0.2364	1.1064
9	0.1191	0.5800	0.1036	0.4735
10	0.1254	0.5893	0.1270	0.5868

Figure 23 shows the plot of the normalized pullout strength with respect to the compressive force.

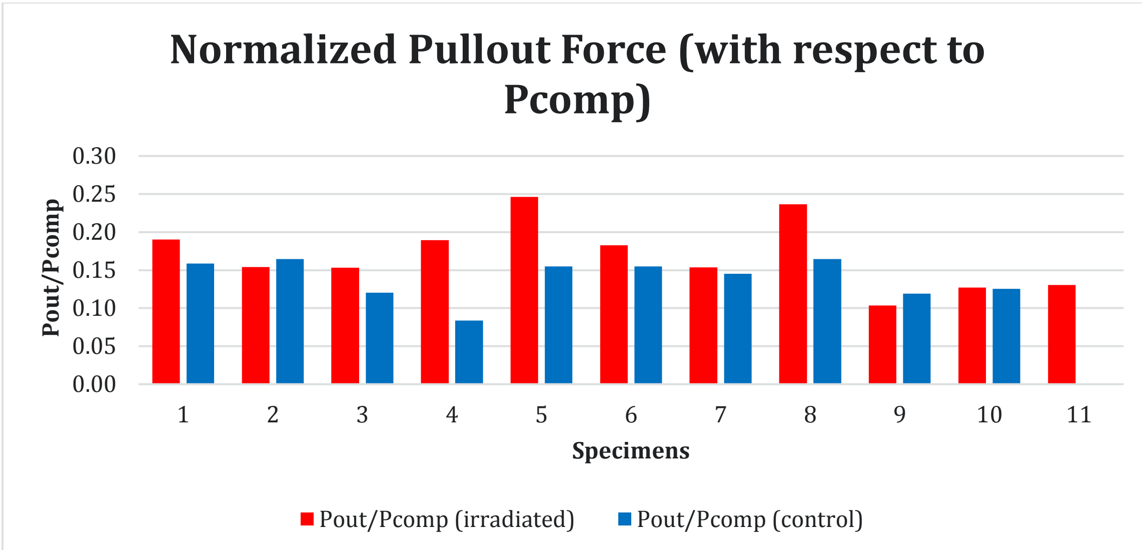

Figure 23. Normalized Pullout Strength with Respect to Compressive Force

The average values for the normalized pullout force with respect to the compressive force for both the control and irradiated batches are 0.14 and 0.17, respectively. The standard deviation of the control batch is 0.03 and irradiated batch is 0.04. Between the control and irradiated batch, the standard deviation is 0.015.

The plot of the normalized pullout strength with respect to the compressive strength is shown in Figure 24.

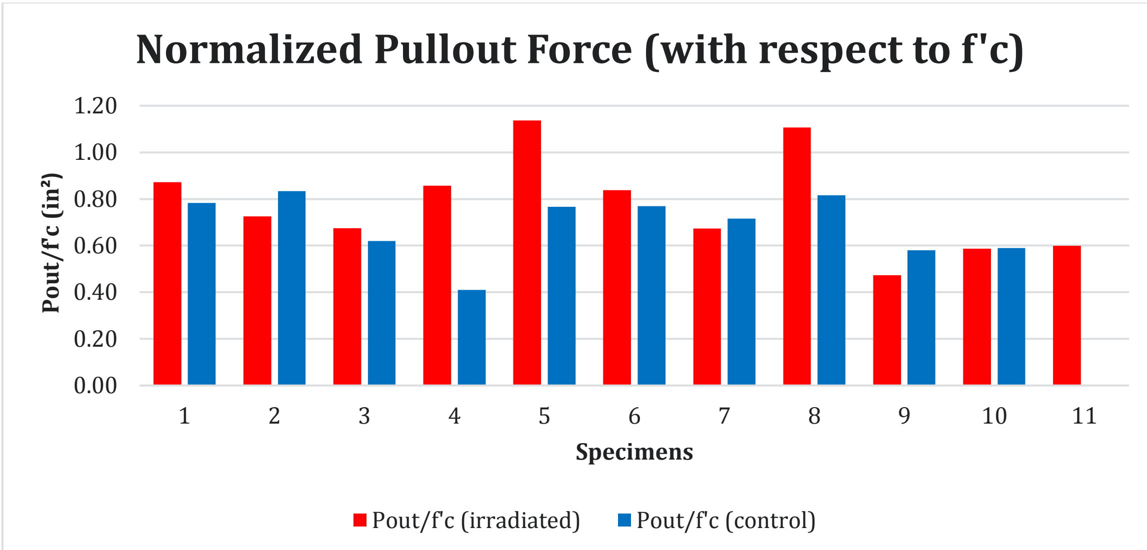

Figure 24. Normalized Pullout Strength with Respect to Compressive Strength

The normalized pullout strength with respect to the compressive strength of the control batch is 0.69 and the average of the irradiated batch is 0.78 with a standard deviation of 0.13 and 0.20, respectively. The standard deviation between the control and irradiated batch is 0.044.

4.4 Average and Standard Deviation of Results

In summary, the average and standard deviation of the pullout strength, compressive force, compressive strength, and normalized values are shown in Table 12.

Table 12. Average and Standard Deviation Values

Averages	Control Specimen	Irradiated Specimen	Standard Deviation
P_{out} (lbs)	5,034	5,005	14.6
P_{comp} (lbs)	36,579	30,388	3,095
f'_c (psi)	7,410	6,652	379
P_{out} / P_{comp}	0.14	0.17	0.02
P_{out} / f'_c (in^2)	0.69	0.78	0.04

These values show that the pullout strength, compressive force, and compressive strength of the control batch is greater than the irradiated batch. The standard deviations of the pullout strength and compressive strength are relatively small showing a similarity in each specimens' strengths.

Furthermore, the percent difference of the above values are calculated to show the range that the control varies from the irradiated. The percent difference is calculated as shown in Equation (5).

$$Percent\ Difference\ (\%) = \frac{Control\ value - Irradiated\ value}{Control\ value} \qquad (5)$$

Table 13 shows the calculated percent difference.

Table 13. Percent Difference of Results

	Percent Difference (%)
P_{out} (lbs)	0.58 %
P_{comp} (lbs)	16.92 %
f'_c (psi)	10.23 %
P_{out} / P_{comp}	- 21.97 %
P_{out} / f'_c (in^2)	- 12.82 %

The results in the above table show that the control batch pullout strength, compressive force, and compressive strengths are greater than those of the irradiated batch. The normalized results are negative because the values for the irradiated batch are larger due to smaller compressive strengths and forces.

Once all the tests are completed, the values recorded, and the corresponding calculations made, the final conclusions are drawn.

4.5. Summary and Conclusion

The first test to occur is the exposure to gamma radiation of the second batch of specimens. The operators at the IAC calculate the number of pulses needed to reach 2 x 10^7 rads of gamma radiation to be 64,815. The average value of pulses received by the ten irradiated specimens is 64,826 pulses with a standard deviation of 20.19 pulses. Compared to the total number of pulses needed to reach the desired dose, the average and standard deviation are well within a range and do not significantly alter any further results.

CHAPTER 4 – LABORATORY TESTING RESULTS

The pullout test of the specimens follows the testing at the IAC. The irradiated specimens are found to have an average pullout strength of approximately 5,005 lbs. with a standard deviation of 804 lbs. The control specimens reach an average pullout strength of 5,034 lbs. with a standard deviation of 928 lbs. The percent difference between the irradiated specimens and the control is 0.58 % with the control batch having the greater pullout strength. These results show that the irradiated specimens' pullout strength is smaller than that of the control, but only slightly. The control batch also seems to have a wider range of pullout strengths and are not as consistent as the irradiated batch. A few reasons for these deviations may be as follows:

- The installation of the components varies for each specimen. The location of the hole drilled for the anchor bolt is not in the very center of the cylinder, and is not exactly at a depth of one inch. The anchor bolt is installed at an angle and not directly vertical despite using a level.
- The strength of the bond between the epoxy and the concrete varies based on the strength of the concrete, which is based on the mix. The concrete mix is made in several batches for both the control and irradiated specimens due to the size of the mixing barrel. This results in small errors on the measurements of the components needed to make the concrete, which in turn makes a small difference in the water to cement ratio or aggregate ratio. This causes the epoxy-concrete bonds to be weaker or stronger relative to the strength of the concrete.

- The Tinius Olsen machine and other equipment used is not calibrated correctly.

The final test is to find the compressive strength of the concrete. The specimens are cast as 6” x 12” cylinders and are cut by a wet saw to 2” x 2” cubes. The average area of the irradiated and control specimens is 4.06 in^2 and 4.39 in^2, respectively. The average force needed to crush the irradiated specimens is 30,388 lbs. The average compressive force for the control specimens is 36,579 lbs. After applying a conversion factor to estimate the 28-day strength from the 103-day strength, the resulting compressive strength of the irradiated batch is 6,652 psi with a standard deviation of 1,011 psi. The compressive strength of the control batch is 7,410 psi with a standard deviation of 1,096 psi. The percent difference between the two compressive strengths is 10.23 % with the control specimens having the greater strength. Even though the compression specimens are cut from the bottom of the cylindrical specimens where there is no direct exposure to radiation, the high temperature affects the whole cylinder resulting in the loss of water. These results coincide with the literature review studies that show the strength of concrete decreasing with increased exposure to radiation and high temperatures. Even though the standard deviations are not small, they are approximately the same which goes to show the differences that come from mixing concrete in several batches. Some more deviations are as follows:

- The size and of the specimens varies. This is based on the accuracy the operator of the wet saw has in cutting the cylinders into cubes. Also, by using a wet saw to cut the cubes, the dimensions are not all equal, and there are jagged or rounded edges. In other words, the specimens are not cut into perfect cubes.

- The loading rate for the compression testing varies per specimen since the equipment used is hard to set to and maintain a specific load rate. This results in a small amount of dynamic loading in addition to static loading.

For some further comparison, the pullout strength is normalized based on both the compressive force and compressive strength of the concrete. The irradiated specimens show higher values for both of these normalizations due to the fact that the pullout strength is slightly lower than the control, but the compressive strength is significantly less. This also results in negative percent differences of – 21.97 % and – 12.82 % for the pullout strength normalized to the compressive force and compressive strength, respectively.

Even though the normalized values for the irradiated specimens are greater than those of the control specimens, the overall pullout strengths and compressive strengths of the irradiated specimens are smaller than those of the control batch, showing that exposure to radiation negatively affect the strength of concrete, steel, and epoxy.

The selection on the size of anchor bolts used in the testing is based solely on availability and price. It is wise to do further testing on differing sizes of anchor bolts, both in diameter and length, since there are not many specifications that require an embedded depth of only one inch. It is assumed that a greater depth is needed in order to meet the required code.

CHAPTER 5 – CONCLUSION

5.0 Introduction

This study analyzes the impact of gamma radiation on the pullout strength of epoxy-bonded anchors in concrete. By following the correct ASTM standards and guidelines, specimens are made and tested. The results of these tests are given in Chapter 4. This chapter discusses the results and makes the appropriate interpretations and conclusions of the data, along with further research recommendations.

5.1 Summary and Conclusions

The effect of 2 x 10^7 rads of gamma radiation on ten prepared specimens containing an anchor bolt bonded to concrete by epoxy is determined in this study. These results are compared to ten control specimens. The following sections review and interpret the results obtained from testing.

5.1.1 Compressive Strength Summary

The testing of both the control specimens and the irradiated specimens show an average compressive strength of 7,410 psi and 6,652 psi, respectively. The percent difference between these two is found to be 10.23 %, with the control specimens having the greater compressive strength. As the existing literature shows, these results are to be expected. One possible reason for such a large decrease in compressive strength is due to the evaporation of water and dehydration of the concrete due to the high temperatures reached during the radiation exposure. Even though the temperature during the radiation exposure test is kept within 100°C, as recommended by Naus in his review regarding the effects of temperature on concrete (2005), the loss of water in the specimens still occur. The decreased strength of concrete after radiation is a concern in this study since the pullout strength of the epoxy-bonded anchors is directly related to the strength of the concrete due to the bonds formed between the epoxy and concrete. As such, it is recommended that water reducing agents be used in further studies to reduce the water content in the concrete specimens while maintaining workability so that the amount of water lost during radiation exposure is not as significant. Another possible reason for the difference in compressive strength is due to the different casting dates of the concrete specimens, and also that the samples are not selected randomly.

5.1.2 Pullout Strength Summary

Despite a significant decrease in compressive strength of the irradiated specimens compared to that of the control specimens, it is seen that the percent difference in the pullout strength of the control specimens is only greater than that of the irradiated specimens by 0.58 %. This value does correspond with the existing literature that radiation (gamma radiation in this case) combined with higher temperatures negatively affects the mechanical properties and strengths of concrete, steel anchors, and epoxy. This study finds that the difference between the pullout strength of the irradiated specimens and the control specimens is quite small, and it is recommended that the use of these products in nuclear environments is not deterred.

CHAPTER 5 – CONCLUSION

In order to normalize the pullout strength to the compressive strength of each specimen, a ratio is found by dividing the pullout strength by the compressive strength. The ratios for both the control and irradiated specimens are 0.689 and 0.777, respectively. The difference between the two gives a value of –12.82 %, with the irradiated specimens having the larger ratio. The normalized results give larger values for the irradiated specimens due to the fact that their compressive strength is so much lower than the control specimens. As such, the normalized values do not accurately represent the negative effects of gamma radiation on the epoxy strength of the specimens.

In conclusion, it is found that radiation *does* negatively affect the strengths of the epoxy-bonded anchors in concrete, but the effect of the radiation on the epoxy pullout strength is small enough to not deter the use of these components in nuclear settings.

5.2 Further Research and Recommendations

Throughout the course of this research, three areas where the research needs to be handled differently are identified. First of all, a schedule of when and where everything is going to take place is needed in order to make sure the research runs smoothly. This way all the preparation and testing or specimens are set for a specific day, and there is little or no wait time for the specimens to simply sit in the lab. Secondly, more test specimens with a wide range of anchor bolt sizes and concrete strengths for both the control and irradiated batches need to be made in order to give more accurate and precise results. Lastly, a random population of specimens, all cast on the same day, need to be selected for both the control and irradiated batches in order to give a better unbiased representation of the data.

Additional items that warrant consideration are:

- Vibration analysis
- Cyclic loading/fatigue testing
- Greater embedment depth (larger anchor bolts)
- Same test with different types of concrete and with higher temperatures

The reasoning for suggesting a vibration analysis is based on the fact that the machinery at the nuclear facilities cause slight or major vibrations based on their functions, and it is sensible to determine the ability of the concrete, steel, and epoxy to withstand these vibrations. Also, here in Idaho, the Idaho National Laboratory (INL) is located in a seismically active zone, so it is also prudent to test for cyclic loading and fatigue failures.

As for testing greater embedment depths, it is assumed that code requires greater depth in order to stabilize machinery and meet all other requirements. As such, it is wise to do further testing of irradiated specimens using larger anchors embedded at greater depths.

One last suggestion for further research topics is to test different mixes of concrete, different epoxy types/brands, and test at temperatures higher that 100°C. The reasoning for testing different mixtures of concrete and epoxies is that the same mix and epoxy is not always used. In most cases, the location and available resources determine the type of concrete that are made and the epoxy that is purchase. Also, as stated previously, the effects of radiation on concrete include the loss of water, which decreases the overall compressive strength. As such, it is sensible to test several different mixes using different additives/admixtures and their combinations. As for testing at higher temperatures, it is not probable that the highest temperature reached at a nuclear facility is 100°C, especially in the case of a fire or a situation where the machinery/equipment overheats. In this case, it is prudent to know how the concrete, steel, and epoxy react to these extreme temperatures.

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APPENDICES

APPENDIX A: CONTROL PULLOUT SPECIMENS (INITIAL AND FINAL)

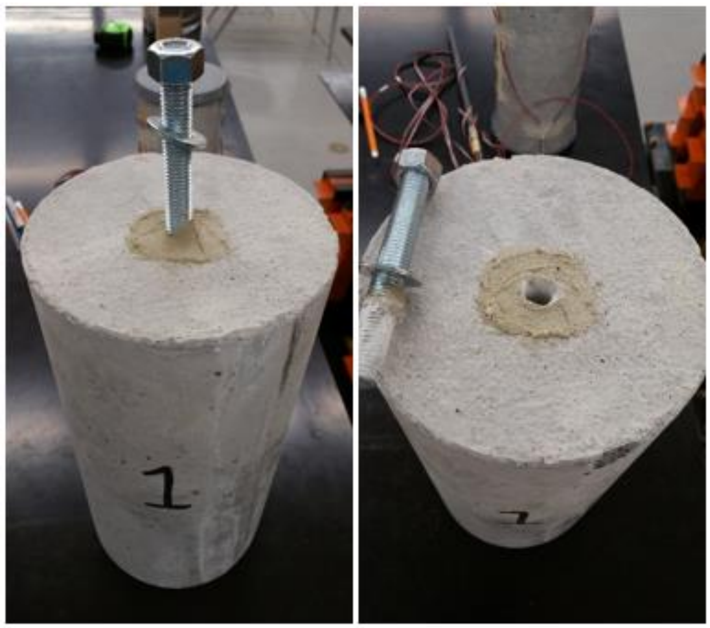

Figure A 1. C-1 Before and After Pullout Test

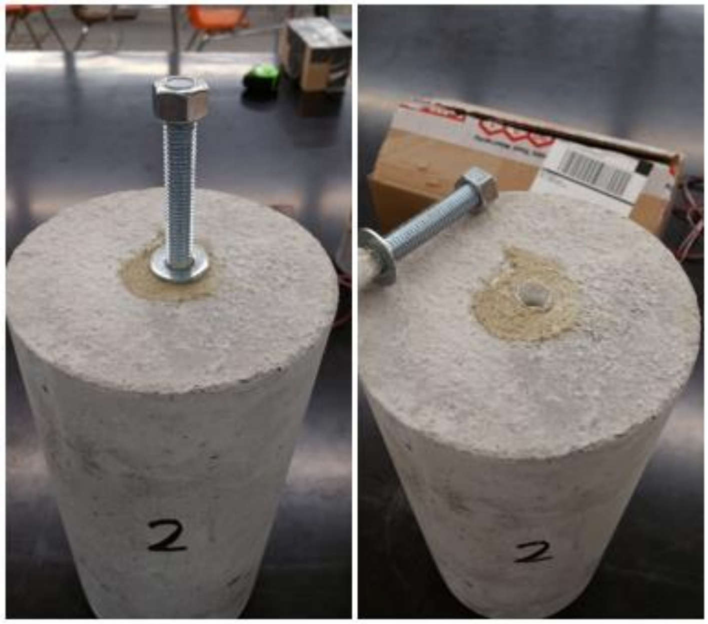

Figure A 2. C-2 Before and After Pullout Test

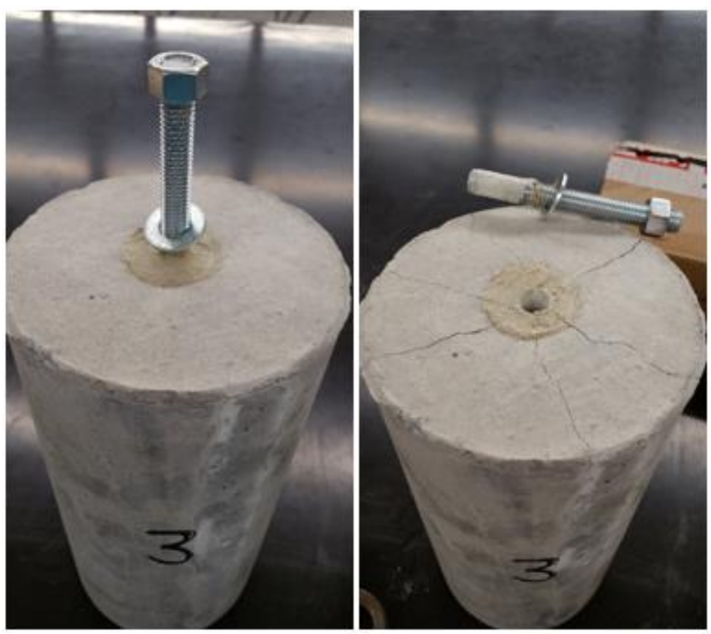

Figure A 3. C-3 Before and After Pullout Test

Figure A 4. C-4 Before and After Pullout Test

Figure A 5. C-5 Before and After Pullout Test

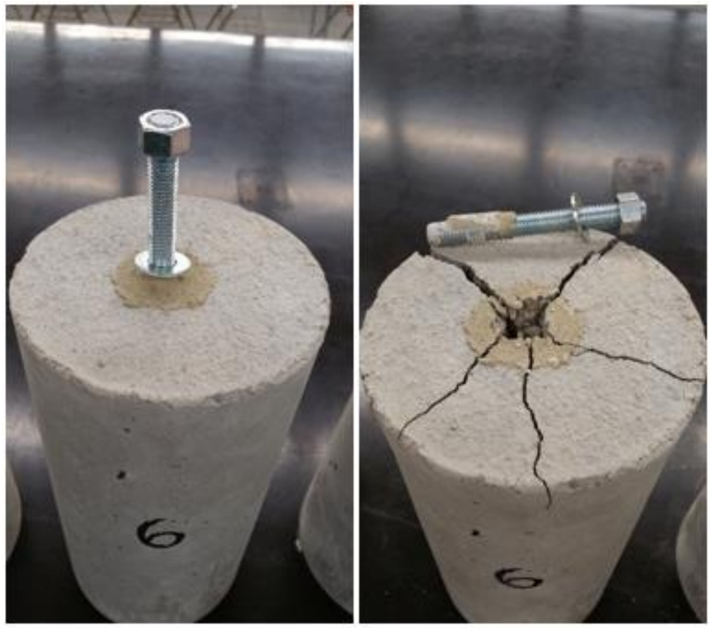

Figure A 6. C-6 Before and After Pullout Test

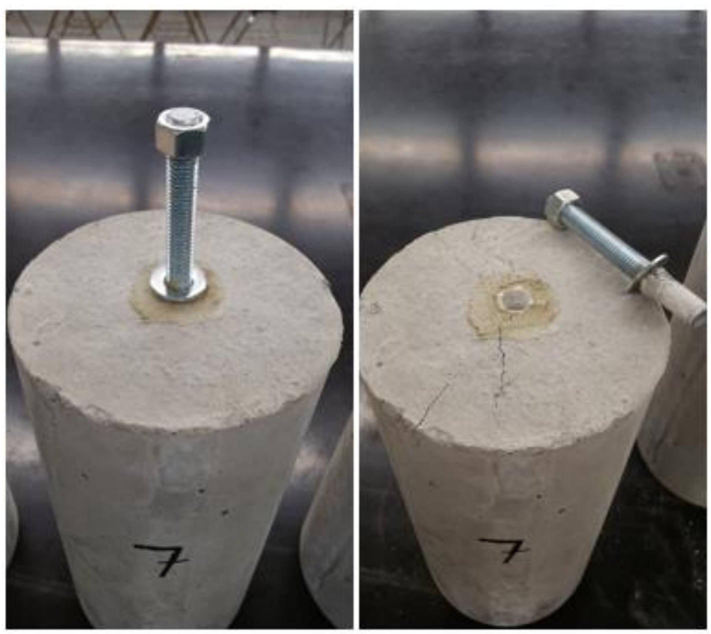

Figure A 7. C-7 Before and After Pullout Test

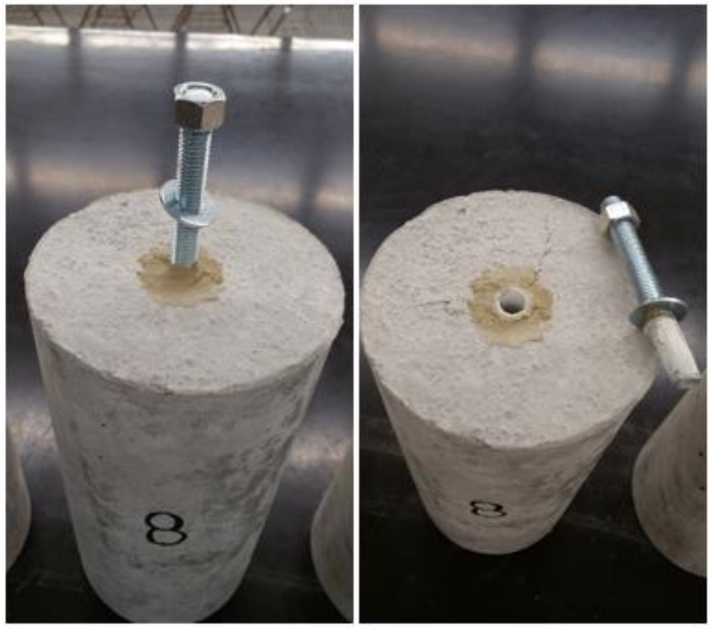

Figure A 8. C-8 Before and After Pullout Test

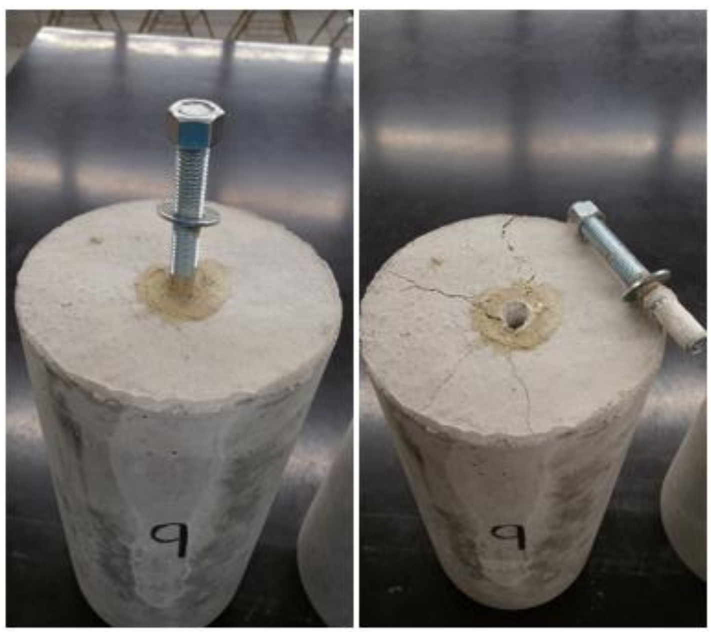

Figure A 9. C-9 Before and After Pullout Test

Figure A 10. C-10 Before and After Pullout Test

APPENDICES

APPENDIX B: IRRADIATED PULLOUT SPECIMENS (INITIAL AND FINAL)

Figure B 1. I-1 through I-10 Before Pullout Test

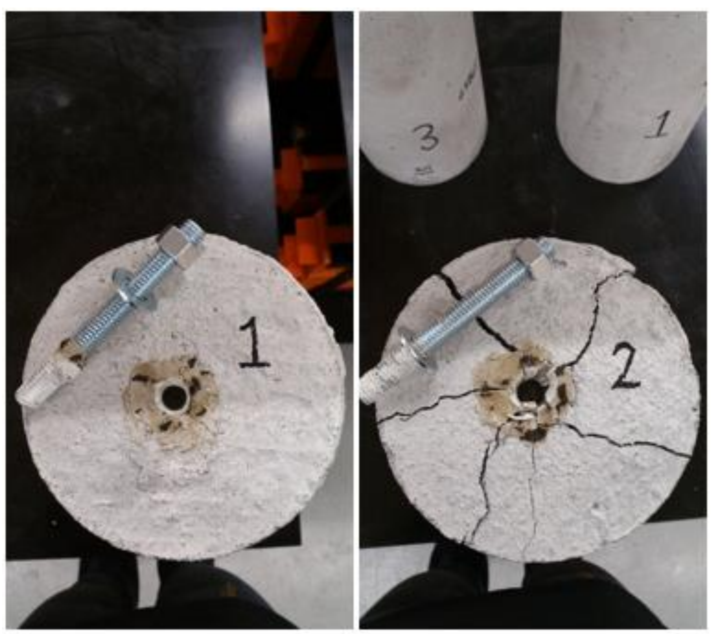

Figure B 2. I-1 and I-2 After Pullout Test

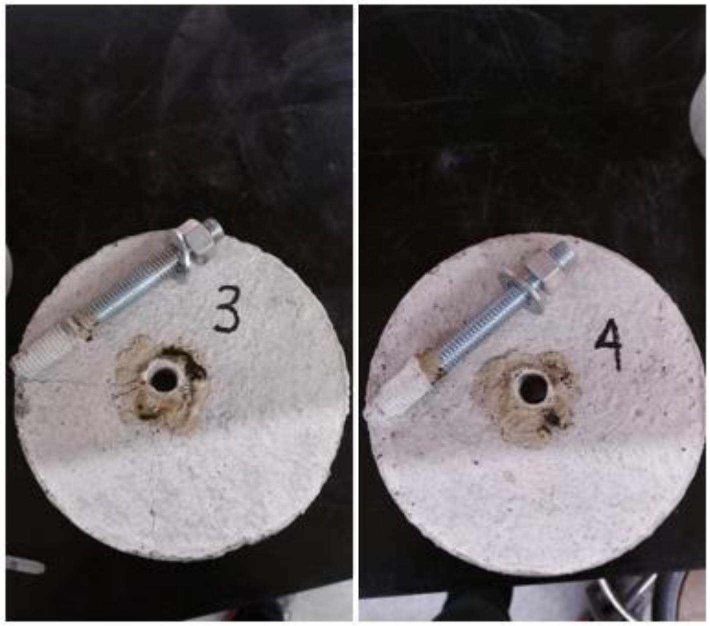

Figure B 3. I-3 and I-4 After Pullout Test

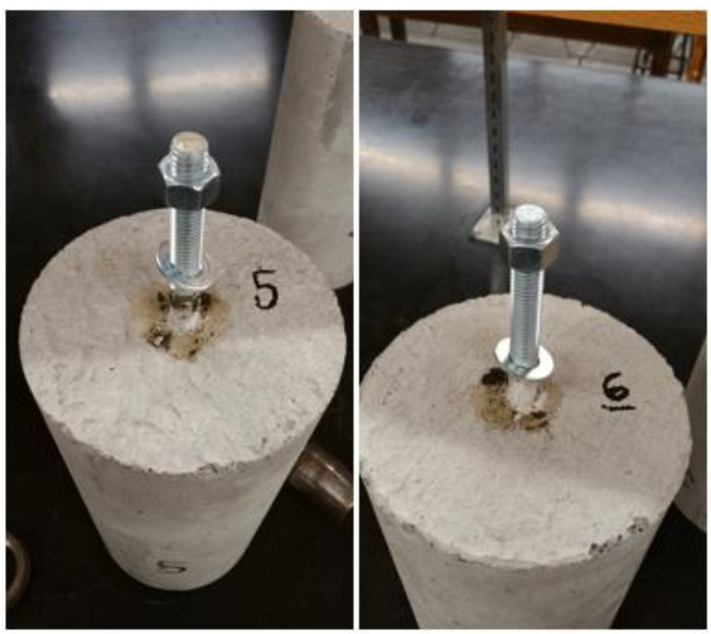

Figure B 4. I-5 and I-6 After Pullout Test

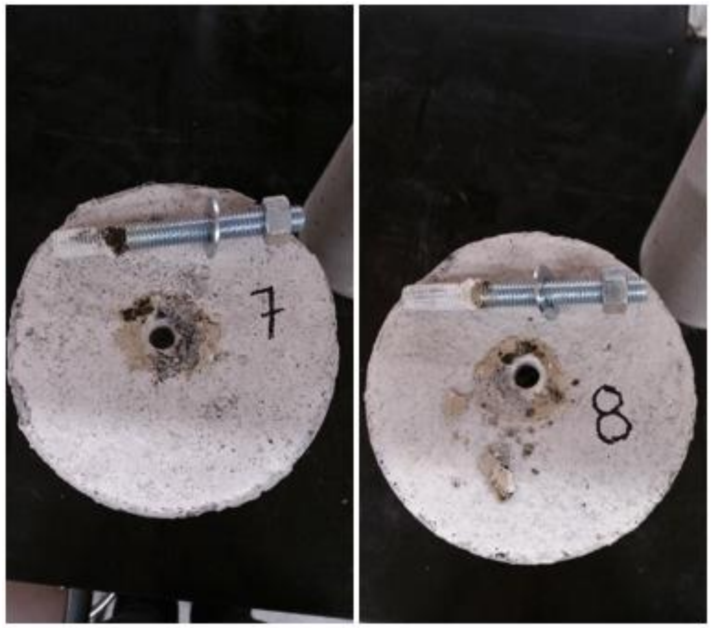

Figure B 5. I-7and I-8 After Pullout Test

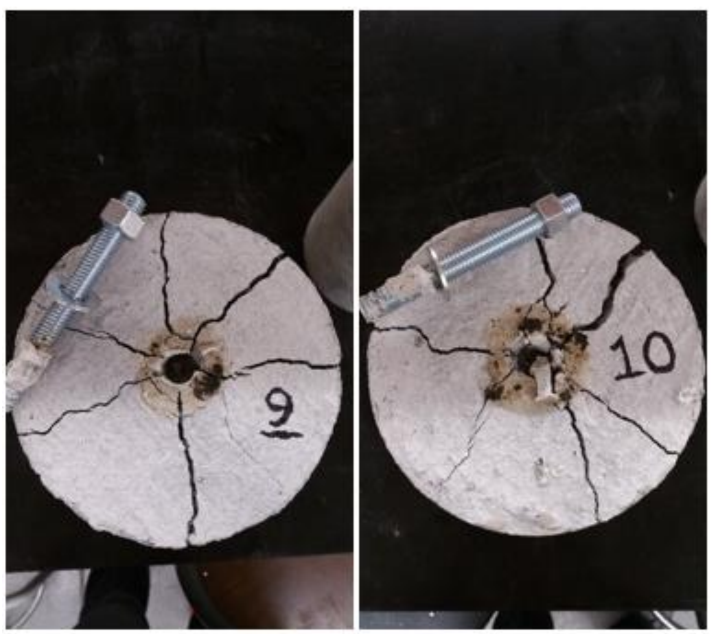

Figure B 6. I-9 and I-10 After Pullout Test

APPENDICES

APPENDIX C: CONTROL COMPRESSION SPECIMENS (INITIAL AND FINAL)

Figure C 1. C-1 Before and After Compression Test

Figure C 2. C-2 Before and After Compression Test

Figure C 3. C-3 Before and After Compression Test

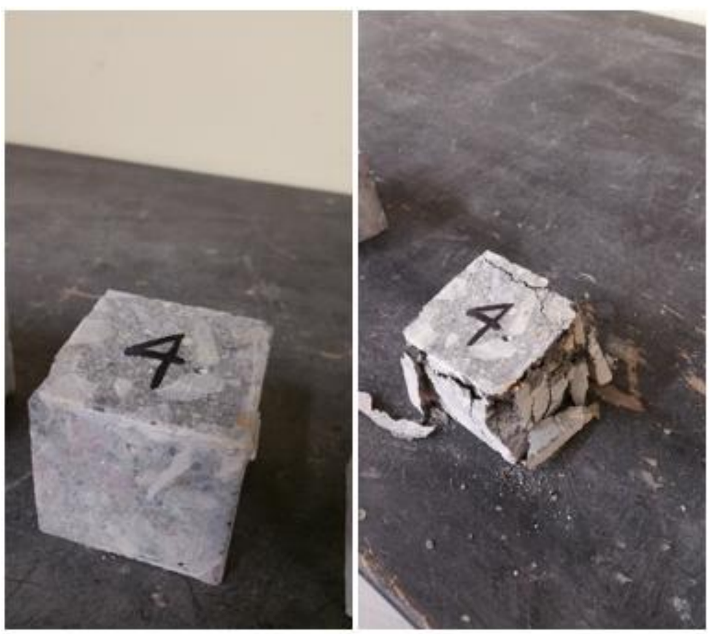

Figure C 4. C-4 Before and After Compression Test

Figure C 5.C-5 Before and After Compression Test

Figure C 6. C-6 Before and After Compression Test

Figure C 7. C-7 Before and After Compression Test

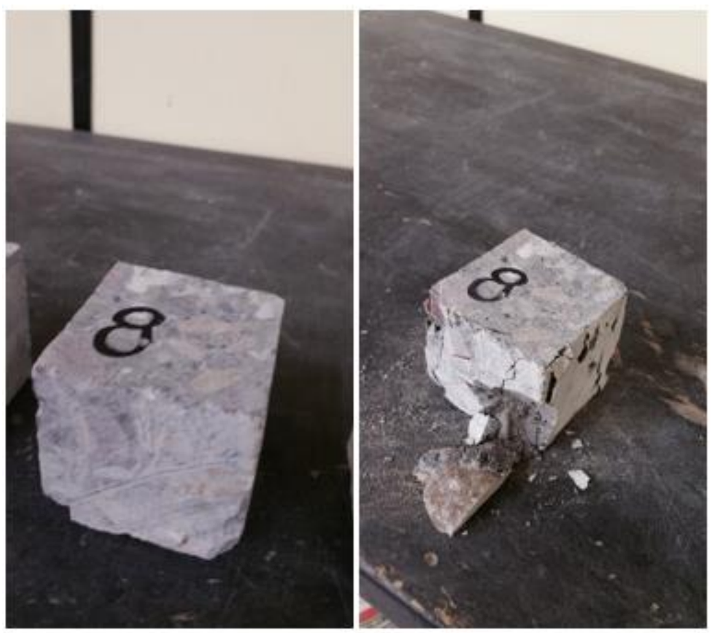

Figure C 8. C-8 Before and After Compression Test

Figure C 9. C-9 Before and After Compression Test

Figure C 10. C-10 Before and After Compression Test

APPENDIX D: IRRADIATED COMPRESSION SPECIMENS (INITIAL AND FINAL)

Figure D 1. I-1 through I-10 Before Compression Test

Figure D 2. I-1 and I-2 After Compression Test

Figure D 3. I-3 and I-4 After Compression Test

Figure D 4. I-5 and I-6 After Compression Test

Figure D 5. I-7 and I-8 After Compression Test

Figure D 6. I-9 and I-10 After Compression Test

APPENDICES

APPENDIX E: SCHEDULE/GANTT CHART

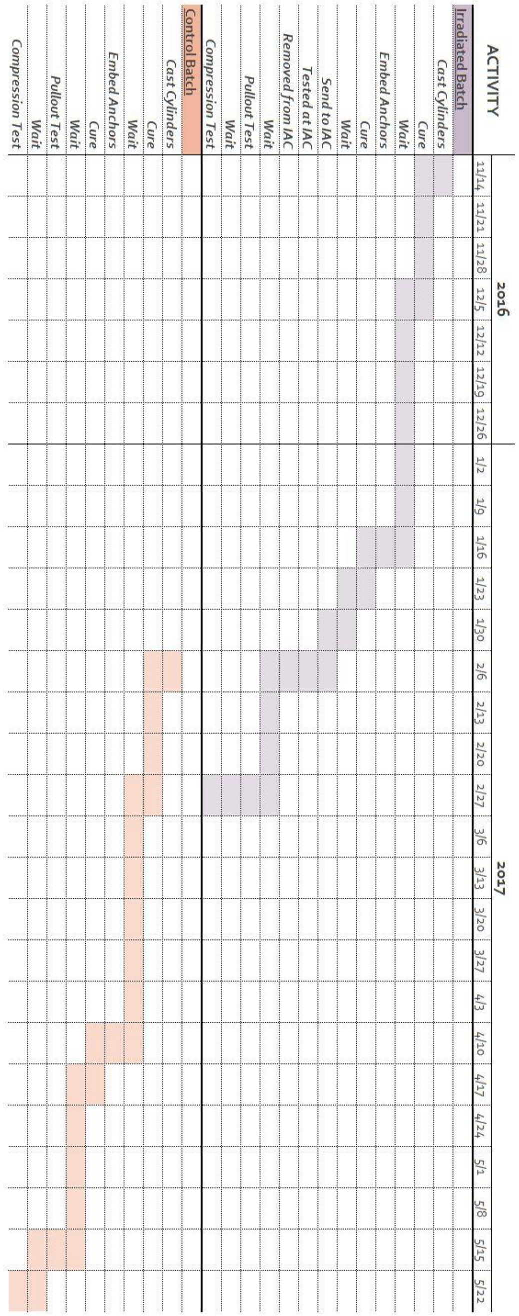

Figure E 1. Research Schedule

APPENDIX F: CONTROL SPECIMENS' DATA

CONTROL CONCRETE SPECIMENS

Specimen	Final Weight (lbs)	Width (in)	Thickness (in)	Area (in²)	Compression Force, Pcomp (lbs)	Cure Time, t (days)	Conversion Factor	Compression Strength, fct (psi)	Control Compression Strength, f'c (psi)	Control Pullout Strength, Pout (lbs)	Pout/f'c (control)	Pout/Pcomp (control)
1	28.595	2.090	2.100	4.389	28,330	103	1.12507	6,454.77	5,737.23	4,496.0	0.7837	0.1587
2	28.495	2.147	2.096	4.500	32,110	103	1.12507	7,135.38	6,342.17	5,287.2	0.8337	0.1647
3	28.675	2.183	2.094	4.571	39,760	103	1.12507	8,697.93	7,731.03	4,787.1	0.6192	0.1204
4	28.655	2.085	2.088	4.353	37,610	103	1.12507	8,639.07	7,678.70	3,146.7	0.4098	0.0837
5	28.575	2.061	2.135	4.400	42,970	103	1.12507	9,765.39	8,679.82	6,653.6	0.7666	0.1548
6	28.295	2.069	2.134	4.415	29,740	103	1.12507	6,735.75	5,986.97	4,609.2	0.7699	0.1550
7	28.625	2.116	2.075	4.391	43,470	103	1.12507	9,900.47	8,799.89	6,305.3	0.7165	0.1450
8	28.640	2.074	2.123	4.403	32,520	103	1.12507	7,385.70	6,564.67	5,357.2	0.8161	0.1647
9	28.445	2.097	2.064	4.328	39,460	103	1.12507	9,116.94	8,103.45	4,700.3	0.5800	0.1191
10	28.400	2.061	2.026	4.176	39,820	103	1.12507	9,536.39	8,476.27	4,994.8	0.5893	0.1254
Average	28.54	2.10	2.09	4.39	36,579.00			8,336.78	7,410.02	5,033.74	0.6885	0.1392
Standard Deviation	0.12	0.04	0.03	0.10	5,192.13			1,233.24	1,096.14	928.09	0.1281	0.0250
Variance	0.01	0.00	0.00	0.01	26,958,209.00			1,520,871.42	1,201,530.35	861,352.79	0.0164	0.0006

* Conversion Factor = t/(4+0.85t)

Figure F 1. Control Specimens' Data

APPENDIX G: IRRADIATED SPECIMENS' DATA

IRRADIATED CONCRETE SPECIMENS

Specimen	Pulses	Initial Weight (lbs)	Final Weight (lbs)	% Change in Weight	Width (in)	Thickness (in)	Area (in^2)	Compression Force, Pcomp (lbs)	Cure Time, t (days)	Conversion Factor	Compression Strength, fct (psi)	Irradiated Compression Strength, f'c (psi)	Irradiated Pullout Strength, Pout (lbs)	Pout/f'c (irradiated)	Pout/Pcomp (irradiated)
1	64,822	28.79	28.85	-0.20%	2.026	2.011	4.074	24,450	103	1.12507	6,001.051	5,333.94	4,650.00	0.8718	0.1902
2	64,815	28.66	28.65	0.04%	2.043	2.050	4.188	33,190	103	1.12507	7,924.740	7,043.79	5,110.00	0.7255	0.1540
3	64,825	28.44	28.45	-0.04%	1.986	1.970	3.912	32,350	103	1.12507	8,268.540	7,349.37	4,960.00	0.6749	0.1533
4	64,815	28.62	28.60	0.06%	2.038	1.973	4.021	27,750	103	1.12507	6,901.313	6,134.13	5,260.00	0.8575	0.1895
5	64,825	28.48	28.50	-0.06%	2.020	2.031	4.103	22,300	103	1.12507	5,435.551	4,831.31	5,490.00	1.1363	0.2462
6	64,819	28.44	28.45	-0.04%	2.024	2.018	4.084	34,960	103	1.12507	8,559.330	7,607.83	6,380.00	0.8386	0.1825
7	64,826	28.75	28.75	-0.01%	2.003	1.942	3.890	28,090	103	1.12507	7,221.403	6,418.64	4,320.00	0.6730	0.1538
8	64,889	28.57	28.55	0.08%	2.032	2.047	4.160	26,350	103	1.12507	6,334.890	5,630.67	6,230.00	1.1064	0.2364
9	64,816	28.31	28.30	0.03%	2.015	2.016	4.062	34,070	103	1.12507	8,386.998	7,454.66	3,530.00	0.4735	0.1036
10	64,816	28.44	28.45	-0.04%	2.024	2.029	4.107	33,150	103	1.12507	8,072.183	7,174.84	4,210.00	0.5868	0.1270
11	64,823	28.84	28.85	-0.05%	2.021	2.020	4.082	37,610	103	1.12507	9,212.673	8,188.55	4,910.00	0.5996	0.1306
Average	64,826.45	28.58	28.58	-0.02%	2.02	2.01	4.06	30,388.18			7,483.52	6,651.61	5,004.55	0.7767	0.1637
Standard Deviation	20.19	0.16	0.17	0.0007	0.02	0.03	0.09	4,623.73			1,137.78	1,011.30	804.33	0.2001	0.0424
Variance	407.70	0.03	0.03	0.0000	0.00	0.00	0.01	21,378,887.60			1,294,543.23	1,022,724.85	646,952.07	0.0400	0.0018

* Conversion Factor = t/(4+0.85t)

Figure G 1. Irradiated Specimens' Data

APPENDIX H: CONTROL SPECIMENS' GRAPHS

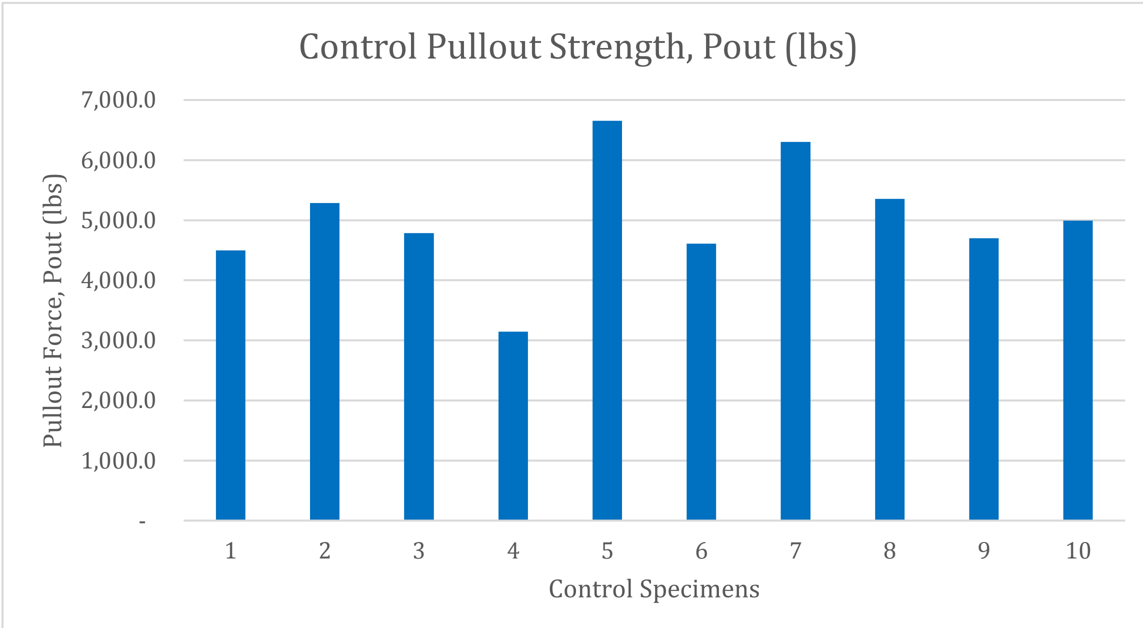

Figure H 1. Control Pullout Strength

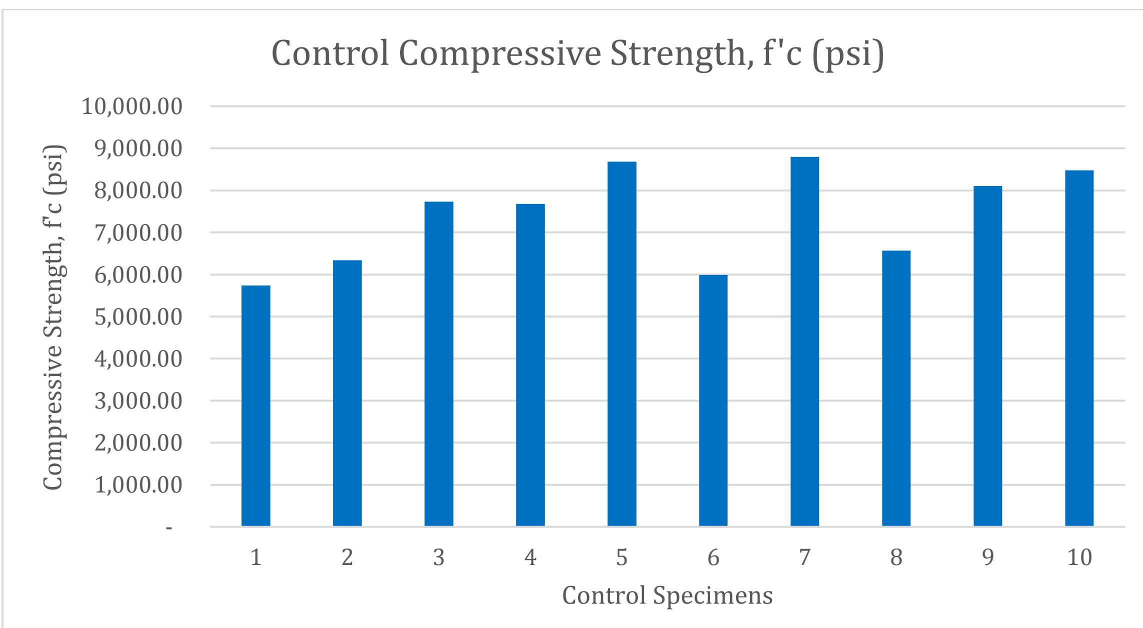

Figure H 2. Control Compressive Strength

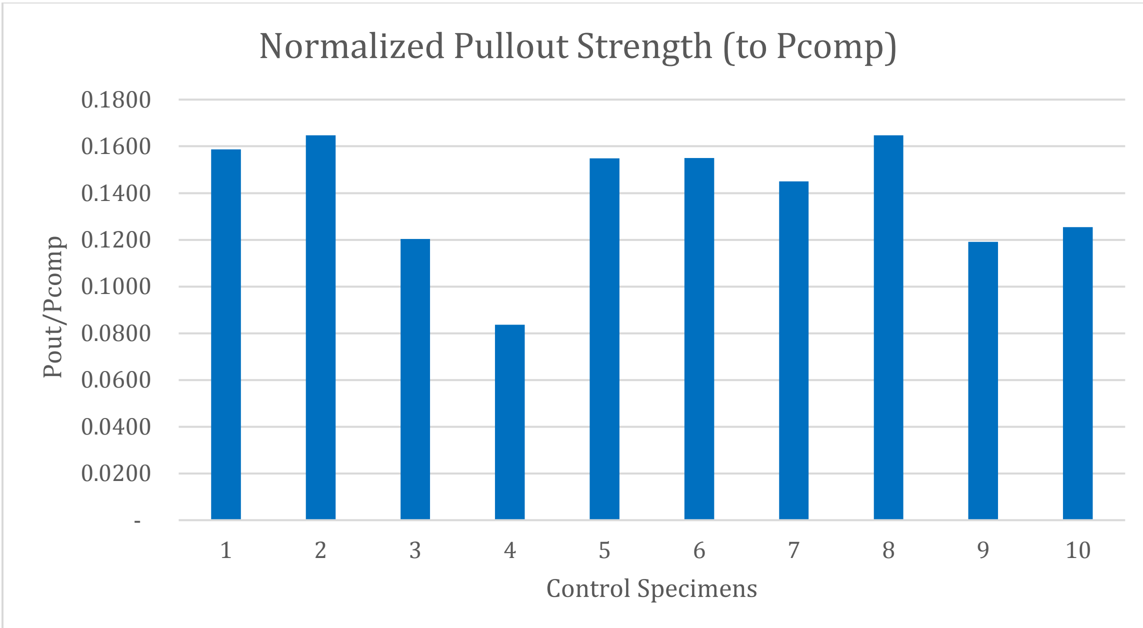

Figure H 3. Control Normalized Pullout Strength to Compressive Force

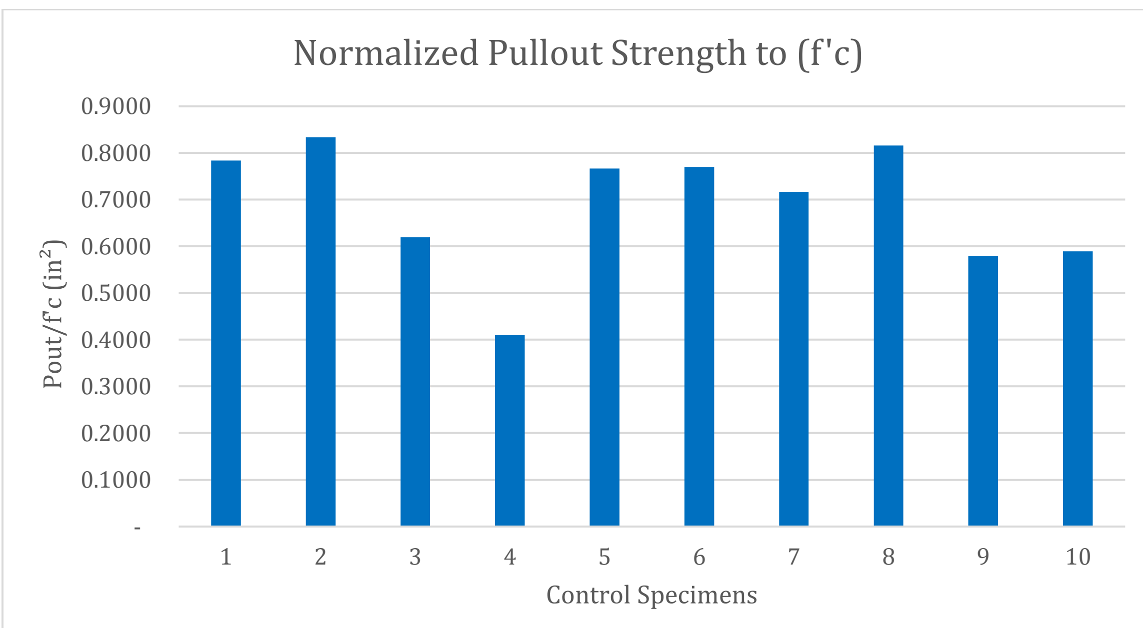

Figure H 4. Control Normalized Pullout Strength to Compressive Strength

APPENDICES

APPENDIX I: IRRADIATED SPECIMENS' GRAPHS

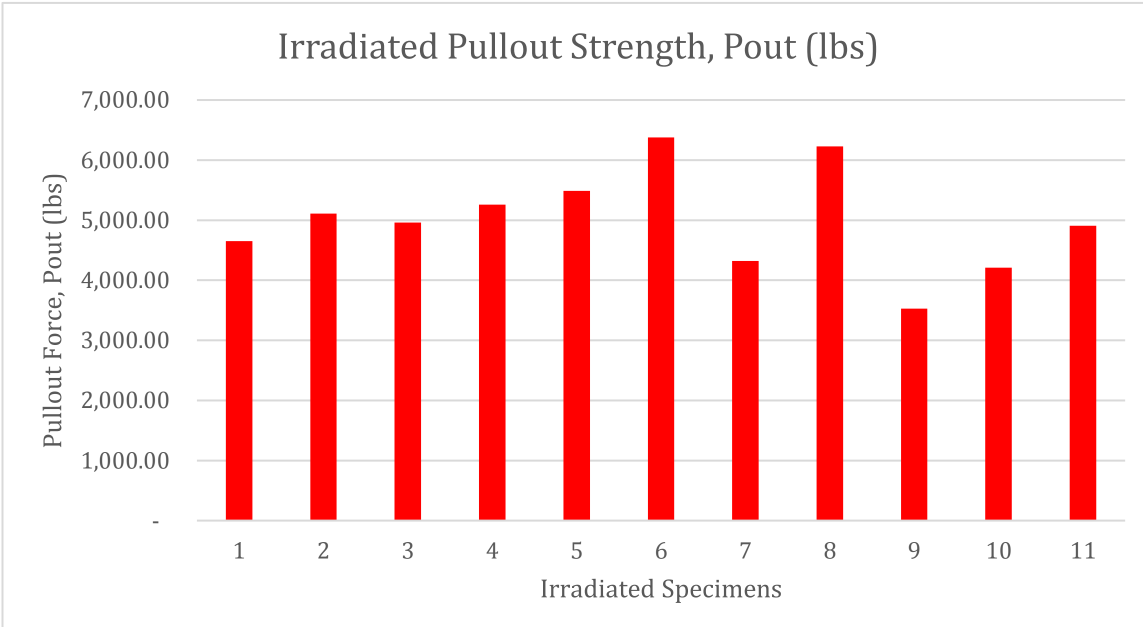

Figure I 1. Irradiated Pullout Strength

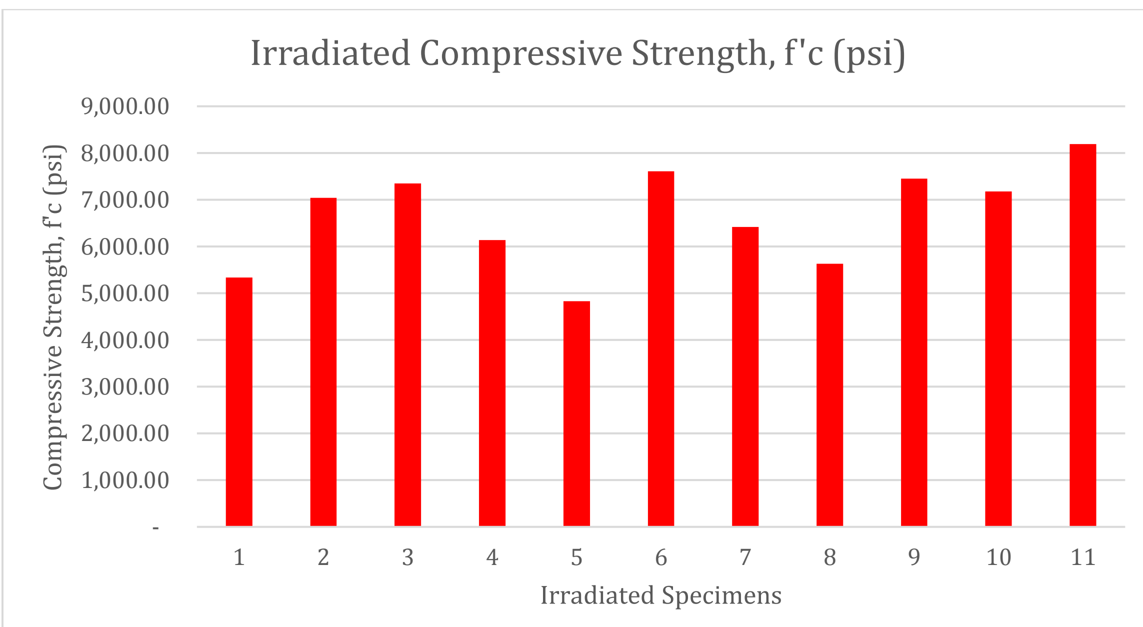

Figure I 2. Irradiated Compressive Strength

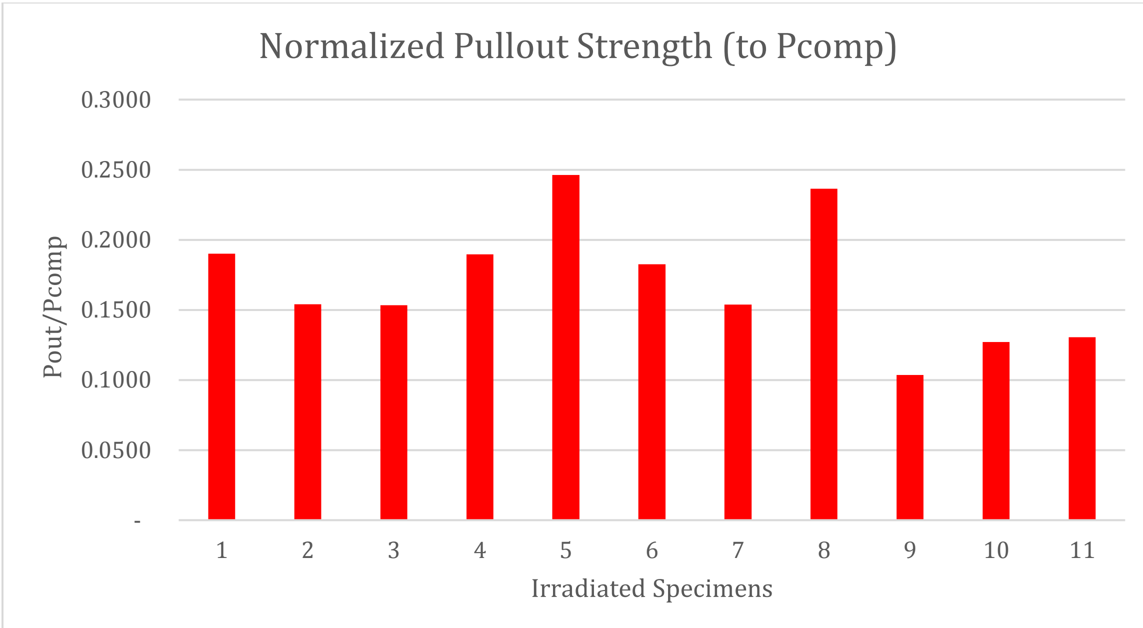

Figure I 3. Irradiated Normalized Pullout Strength to Compressive Force

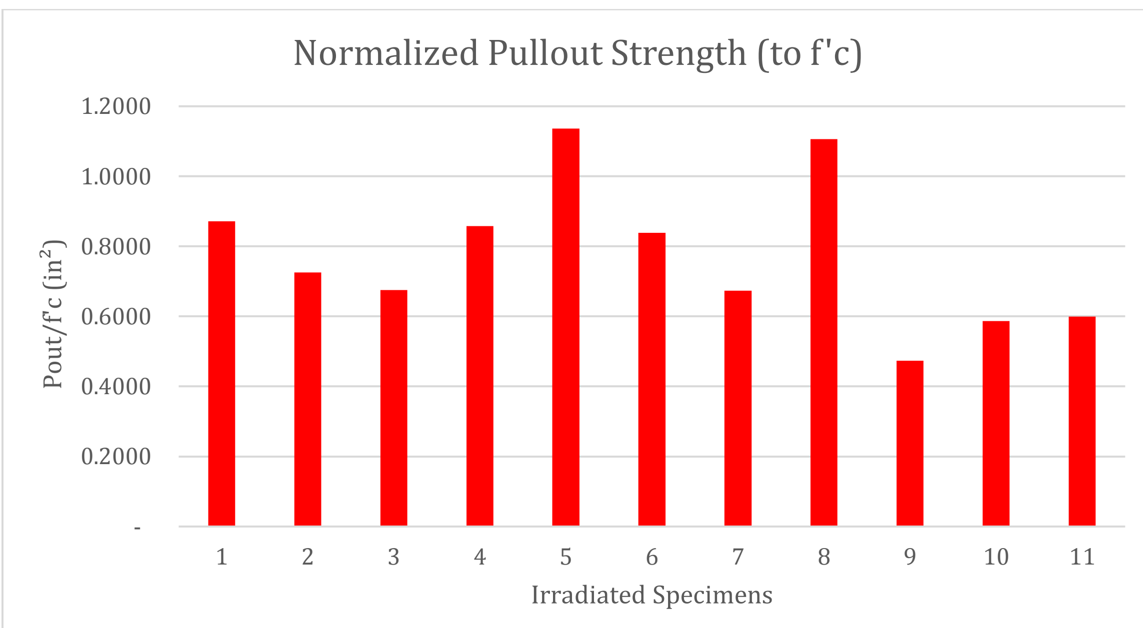

Figure I 4. Irradiated Normalized Pullout Strength to Compressive Strength