Extruded recycled plastic as a partial coarse aggregate in concrete

by

Lauren Costello

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GE Johnson Department of Architectural Engineering and Construction Science
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Approved by:

Co-Major Professor
Katie Loughmiller

Approved by:

Co-Major Professor
Kimberly Waggle Kramer

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Abstract

Concrete usage has reached an all-time high and is only expected to continue to increase as population increased and more areas become industrialized. The natural resources used to make concrete are finite and the consumption of some resources, aggregates in particular, has surpassed the natural rate of renewal (Gu & Ozbakkaloglu, 2016). Replacement materials must be found if concrete is to continue to be used at increasing rates. A possible replacement material for aggregates is recycled plastic materials. This solution would also contribute to the removal of growing amount of plastic from the waste stream. This research examines the application of an extruded plastic replacement coarse aggregate product called Plazrok, developed by the company Enviroplaz. Fresh and hardened properties were observed and recorded of a control mix as well as a 15%, 30%, and 45% replacement rate by volume. The tests performed on the hardened concrete were compression, splitting tensile, and modulus of rupture. A significant change in fresh concrete properties did not occur. As the rate of replacement of the aggregate increased, a decrease in the compression, splitting tensile and modulus of rupture strength was observed. The compression tests give a proportional decrease in strength with the increase in replacement aggregate, 19.1%, 35.9% and 48.1% decrease in compressive strength at 15%, 30%, and 45% replacement, respectively. Equations to calculate the decrease in strength are presented. Tensile splitting and modulus of rupture show decreases in strength but not with the same consistency. Splitting tensile strength at 28-day strength decreased at most 21.9% but the seven-day strength showed the greatest decrease of 46.67%. The modulus of rupture at 28-day strength showed a 7.9%, 12.4%, and 28.5% decrease at 15%, 30%, and 45% replacement, respectively.

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I would like to thank Chaz (Charles) Hill and Midwest Concrete Materials for providing me with the mix design and material for concrete.

I would also like to thank all those who assisted me in the lab with batching and testing the specimens used in this study.

Dedication

I dedicate this to my father and late mother who instilled in me a pursuit of knowledge, strong work ethic, and belief that the world is good but can always be improved. As well as my friends who have inspired me and challenged me to strive for more and have made life worth living.

Chapter 1 - Introduction

Currently "Reduce, reuse, recycle" is a common phrase in the United States and the recycling rate has increased in the United States from less than seven percent in 1960 to 32% in 2019 (US EPA, 2020). Mechanical recycling is the traditional method of recycling, plastic must be sorted, cleaned and heated to form resin pellets which can be used to make new plastic products. This method does not change the chemical make-up or basic structure of the material. Advanced, or chemical, recycling processes can break down plastics into their original molecular building blocks by dissolving them or using heat. The broken-down material can be repurposed to make a new variety of products such as new plastics, industrial chemicals and products, and transportation fuels (*Advanced Recycling | From Single Use to Reuse*, 2020).

Concrete is the most widely used construction material next to water (Bhardwaj & Kumar, 2017). Population growth and increased industrialization will only increase demand for concrete. Concrete is an ideal construction material for its durable and dependable nature. It also provides favorable energy performance in buildings, it can be used in a large variety of forms, designs, and applications, it is affordable, and relatively environmentally friendly (Tarun R. Naik, 2008). Aggregates comprise about 65-80% of concrete by volume and have a considerable influence on the strength, permeability, workability, durability, and other properties (Faraj et al., 2019). As of 2014, approximately 40 billion tons of aggregate was produced worldwide, up from 21 billion tons in 2007, and an expected growth rate to 60 billion tons by 2022 (Kuhlar, 2014) with higher rates of growth in emerging economies, China alone held half of the worldwide new aggregate demand from 2010 to 2015 (Tam et al., 2018). Using a conservative estimate assuming 80% aggregate by volume in a concrete mix, the 40 billion tons of aggregate equates to 50 billion tons of concrete, enough to cover the entire state of Texas

(United States, 268,597 square miles) with a one-inch thick layer of concrete. The availability of high quality aggregates has decreased especially in urban areas where the local aggregates have been striped resulting in a need to travel further to attain aggregates which negatively affects the sustainability of concrete construction (Taffese, 2018).

Work has been done to mitigate the growing amounts of waste in the environment and adding it to concrete mixtures is not a new idea. Different types of waste have been used in the mixtures. Construction and demolition (C&D) waste has been implemented in various levels of use. C&D waste is more readily available in urban areas where construction is almost constant and some developed countries have incentives for using C&D waste. However, in developing countries, lack of regulations and knowledge can lead to poor results and weakened concrete that dissuades others from attempting to implement it (Tam et al., 2018). Different types of recycled plastics, developed using mechanical (traditional) recycling methods have been used for over 25 years. These recycled plastics have been implemented as fine aggregates, coarse aggregates and plastic fibers (Gu & Ozbakkaloglu, 2016).

The substitution of recycled plastic aggregates for traditional aggregates can be a solution to the issues of increasing aggregate usage and plastic waste; using recycled plastic as a replacement for coarse and fine aggregates. This thesis studies the use of a fractional coarse aggregate replacement product, Plazrok by Enviroplaz. Plazrok is unique in that is made up of plastics as well as glass and minerals, all collected from the waste stream. This product has plenty of promise to contribute to solving the two issues mentioned of increasing plastic waste and complicated recycling methods.

To test Plazrok as a partial aggregate replacement, four different mixes of concrete were batched and tested. The concrete mixes were based on the standard commercial interior normal weight concrete mix, this is a non-air-entrained mixture, provided by Midwest Concrete Materials (MCM), with design strength of 4000 psi. The four concrete mixes tested were a control mix with no variations to the original mix design as well as three mixes with 15%, 30%, and 45% coarse aggregate replacement by volume. The details of the mix designs are further discussed in Chapter 3 - Test Setup and Procedure.

Results are presented in Chapter 4 - Test Results. Fresh concrete properties and hardened concrete properties were examined and recorded. There was little change to the overall fresh concrete properties of workability, density, and slump. The hardened concrete properties include compression, tensile splitting, and modulus of rupture. The results of the compression tests showed a proportional inverse decrease in strength as more aggregate was replaced with Plazrok.

Chapter 2 - Literature Review

The goal of this research is to determine if replacing traditional coarse aggregate with the recycled plastic aggregate material, Plazrok, can be viable in a typical indoor concrete mix. If this method is proven to be viable, the application can benefit two different important issues. First, the overuse of natural resources used to make concrete. Second, the growing amount of plastic waste. The factors that will be looked at in the concrete mixes are compression strength, tensile splitting strength, modulus of rupture, and density of the concrete. These factors will be tested on four different mix designs: control with 0% replacement of coarse aggregate by volume, 15% replacement, 30% replacement, and 45% replacement. The factors that were tested and the mix designs are based on previous research done with different recycled plastic aggregate materials.

2.1 Concrete Usage

Concrete is considered a sustainable building material primarily due to its longevity and thermal efficiency. However, the volume of concrete consumed is reaching an unsustainable level. Concrete is comprised of cement, water, coarse and fine aggregates, and admixtures, with the aggregates comprising about 70- 80% of the concrete's volume. Natural aggregates are typically crushed stone, sand, or gravel (Verian et al., 2018). As population increases and more areas are industrializing the demand for concrete is higher than ever and is increasing at an alarming rate. Global aggregate production increased from 21 billion tons in 2007 to 40 billion tons in 2014 with a estimation that global production will reach 66 billion tons by 2030 ("Global Aggregates Growth Examined by GAIN Convenor Jim O'Brien," 2019; Tam et al., 2018). This is almost a 100% increase in consumption in just seven years and another 65% increase from

2014 to 2030. All this while the world population only increased approximately 9% in the same seven year span and an expected 17% increase from 2014 to 2030 (Roser, 2013). This shows that industrialization is proving to be a much larger catalyst in aggregate consumption than population growth alone.

Aggregates are mined from quarries or excavated from water systems. In areas with high demand for aggregates, the rate of usage has surpassed the natural rate of renewal. On average it takes about 1000 years to deposit just one millimeter of sediment which will eventually become rock that can be used as aggregates (*Time and Rocks*, 2021). This is increasing the damage to local ecosystems to a potentially irreversible level (United Nations Environment Programme, 2014). A solution to this problem is to use less aggregate, however, using less concrete is not a viable option. In recent years, the per capita demand for aggregate has grown to 10.7 tons per person per year in the United States. The aggregate industry is expecting a demand in aggregate production in the next 25 years to be equal to the last 100 years. (Robinson, Jr. & Brown, 2021) A possible solution is to partially or fully replace natural aggregates with other materials (Gu & Ozbakkaloglu, 2016).

Many possible aggregate substitutes have been proposed and studied. These possible substitutes include, virgin plastics, recycled plastics, shredded tires, and construction and demolition waste. All of these methods could contribute a significant decrease in the amount of natural aggregates required for construction. Inferior quality of recycled aggregates compared to natural aggregates is a concern in the industry. Therefore, studies must show significant benefits to ensure that alternative materials can become a viable addition to the construction industry.

2.2 Plastic Waste and Recycling

Plastics have become an integral part of our daily living. It is a very favorable material for a very large range of products because of the wide range of properties it can take on. Plastic can be used in small and large applications, has a high strength to weight ratios, high durability, low cost and it is incredibly easy to produce. Plastic has been used in furniture, electronics, medical devices, food packaging, clothing fabrics, building materials, and endless other applications.

Plastics can be categorized into two categories: thermoplastic and thermosetting plastic. Thermoplastic polymers are made by heating the material and molding it into a specific shape for the desired design. Since no changes are made to the material itself and no chemical processes taking place, the material is easily recycled since it can be reheated and remolded into a new product while maintaining its properties. Examples of thermoplastics are polypropylene (PP), polyethylene (PE), nylon, polylactic acid (PA), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). While these plastics can be recycled, sorting and thorough cleaning must happen before the recycling process. Thermosetting plastics, on the other hand, develop a cross-linked structure during processing which changes the properties of the material. This makes the product stronger and more resistant to rises in temperature, but makes it almost impossible to recycle because the polymer molecules form covalent bonds during the heating process, which are very difficult to break. Despite this, thermosetting plastics are used more commonly because the mechanical properties are far superior and have a much higher resistance to changes in temperature. Products that are expected to be exposed to rises in temperature must be made from thermosetting plastics, such as parts in electronics, vehicle parts, microwaveable kitchenware, etc. (Mohan et al., 2021).

Since the 1950s, the production of plastic has increased at a rate higher than almost all other materials (Almeshal et al., 2020). An estimated 300 million tons of plastic are produced each year as of 2019; almost half of which is single use plastic and will go immediately to the waste cycle. Approximately 40% of plastic in the waste cycle goes to landfill, 25% is incinerated, 19% is in unmanaged dumps or leaked out into streets and waterways, 3% is lost or rejected, and only 13% gets recycled. This breakdown is shown in Figure 2-1 (Ritchie & Roser, 2018). Landfilling is considered to be the least ideal method of dealing with plastic waste because increasing amounts of space is required and produces long term pollution issues. Incineration is considered slightly better because it purges of the material, but produces copious amounts of carbon dioxide and releases poisonous chemicals (Gu & Ozbakkaloglu, 2016). Therefore, recycling is the best solution to reduce the overall impact of plastic waste on the environment.

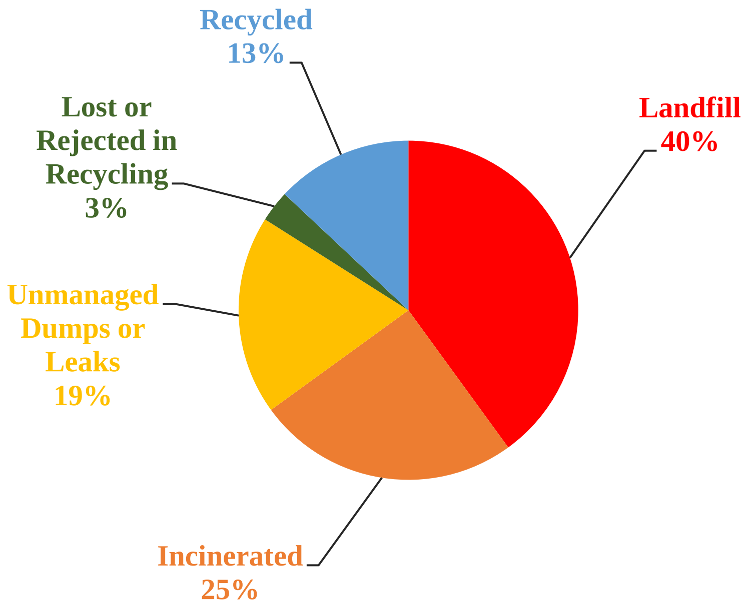

Figure 2-1 Breakdown of Plastic Waste

Plastics are made up of organic compounds and eventually degrade. However, this process, unless catalyzed by ultraviolet radiation, is incredibly slow compared to other organic compounds. The material very slowly loses integrity and eventually breaks down into inorganic molecules, a process called mineralization. This process can take centuries and therefore, not a viable option to eliminate of plastic waste from the environment. Even plastics labeled as "biodegradable" fair slightly better than their conventional counterparts because only a portion of the polymer has the increased rate of degradation (Andrady & Andrady, 2015).

The recycling systems in most of the world are antiquated due to China accepting and processing the majority of the world's plastic recycling for the past several decades. And as a result, other countries have fallen behind in recycling the accumulated plastic waste. As of January 2018, China no longer accepts plastics with the intention to recycle it. Setting up these recycling systems can be cost prohibitive so the development of plants to sort and recycle the plastics has been slow. However, if demand for recycled products is significant, development of plants will occur and make ample recycling systems outside of China (Degnan & Shinde, 2019).

2.3 Recycled Plastic in Concrete

Among the possible recycling methods, the reuse of waste and recycled plastic in the construction industry is considered an ideal method for disposing of plastic waste. This method is superior to many other methods of recycling because it takes advantage of the plastic's natural resistance to degradation and the plastics replace the consumption of virgin construction materials (Gu & Ozbakkaloglu, 2016). Different types of plastic waste have been thoroughly researched and experimented with. These plastic types include polyethylene terephthalate (PET) bottles (Akçaözoğlu et al., 2010; Albano et al., 2009; Ferreira et al., 2012; Frigione, 2010; Kim et al., 2010; Marzouk et al., 2007; Silva et al., 2013), polyvinyl chloride (PVC) pipes (Kou et al., 2009), high density polyethylene (HDPE) (T. R. Naik et al., 1996), thermosetting plastics (Panyakapo & Panyakapo, 2008), mixed plastic waste (Ismail & AL-Hashmi, 2008), expanded polystyrene foam (EPS) (Kan & Demirboğa, 2009), polyurethane foam (Ben Fraj et al., 2010; Mounanga et al., 2008), and glass reinforced plastic (GRP) (Asokan et al., 2010). These studies used waste plastic as replacement aggregate, fillers, or fibers in the cement mortar or concrete after mechanical treatment (Saikia & de Brito, 2014).

2.3.1 Plastic Aggregates and Fibers

Plastics have been implemented into concrete and cement mortars in two main methods, plastic aggregates, used to replace natural aggregates, and plastic fibers, used in fiber-reinforced concrete. Several studies have investigated the differences of concrete's fresh and hardened properties between concrete made with plastic aggregate and concrete reinforced with concrete fibers (Faraj et al., 2019; Pacheco-Torgal et al., 2012; Siddique et al., 2008). However, detailed material properties of the plastics were not provided in these reviews and not all important properties of concrete were included, such as, stress-strain curves, abrasion resistance, and creep (Gu & Ozbakkaloglu, 2016).

Plastic fibers are used in concrete to enhance the mechanical properties and durability of the concrete. Plastic fibers are used in replacement of steel fibers. Plastic fibers are superior to steel fibers in that they are not susceptible to corrosion, have a lower carbon footprint, particularly when the plastic is recycled, have a higher strength to weight ratio, and have a lower price point (Yao et al., 2003).

Inclusion of plastic aggregates affects both the fresh and mechanical properties of concrete. There are two deferring hypotheses on the effect of plastic aggregate on the slump of the concrete. One is that the plastic aggregate decreases the slump of the fresh concrete because of the sharp edges and jagged shape. The other argues that the plastic has a lower absorption capacity so more free water will be present in the concrete mix, increasing slump (Saikia & de Brito, 2014).

2.3.2 Fresh Concrete Properties

Addition of plastic into concrete mixes has an effect on the fresh concrete properties of the concrete. The effect on the fresh concrete properties can indicate an effect on the final mechanical properties of the concrete (Silva et al., 2013).

2.3.2.1 Slump

Inclusion of plastic aggregates affects both the fresh and mechanical properties of concrete. There are two deferring hypotheses on the effect of plastic aggregate on the slump of the concrete. One is that the plastic aggregate decreases the slump of the fresh concrete because of the sharp edges and jagged shape. The other argues that the plastic has a lower absorption capacity so more free water will be present in the concrete mix, increasing slump (Saikia & de Brito, 2014).

2.3.2.2 Unit Weight and Density

The unit weight and bulk specific gravity of plastic aggregates is lower than that of natural, normal weight aggregates. Therefore, the density of concrete mixtures decreases linearly with increased implementation of plastic aggregates (Siddique et al., 2008).

2.3.3 Mechanical Properties

The mechanical properties, such as compressive strength, tensile splitting strength, and modulus of rupture, of the concrete with these replacement materials must be heavily researched and tested to ensure the concrete mix will have the required strength. However, even when these tests are proficiently performed, the samples used in testing are only valid for the exact specifications of the mix, including mixing and batching methods, time and location of curing and moisture content and testing apparatuses on the date of testing (*ASTM Standard C78 / C78M*, 2020).

This paper focuses on recycled plastic as a partial replacement for coarse aggregate. Many studies have been conducted to observe the properties and behavior of concrete when coarse aggregates have been partially or fully replaced by recycled plastic. There are varying results based on the type of plastic used, the method used to recycle the plastic, the size and shape of the recycled aggregate, coatings on the recycled plastic aggregate, as well as the concrete mix itself (Gu & Ozbakkaloglu, 2016).

The strength properties and modulus of elasticity of concrete containing plastic aggregates are always lower than those only containing natural aggregates. Greater replacement rates of plastic aggregate results in further decreases in strength. The decrease in bond strength between the plastic and the cement paste due to the hydrophobic nature of plastic is a possible reason for the decreased strength (Saikia & de Brito, 2012; Siddique et al., 2008).

2.3.3.1 Compressive Strength

The effect of compressive strength of concrete containing plastic aggregates depends on many parameters such as replacement rate of plastic aggregate, water-to-cement ratio (*w/c*) and the type and shape of waste plastic used. Figure 2-2 and Figure 2-3 show the effects of recycled plastic replacement rate on the compressive strength of the concrete as found by existing studies (Akçaözoğlu et al., 2010; Akçaözoğlu & Ulu, 2014; Albano et al., 2009; Asokan et al., 2009, 2010; D. S. Babu et al., 2006; Batayneh et al., 2007; Ben Fraj et al., 2010; Chen & Liu, 2004; Choi et al., 2005; Elzafraney et al., 2005; Ferrándiz-Mas et al., 2014; Ferreira et al., 2012; Frigione, 2010; Galvão et al., 2011; Ge et al., 2013; Haghi et al., 2006, 2006; Herki et al., 2013; Ismail & AL-Hashmi, 2008; Juki et al., 2013; Kan & Demirboğa, 2009; Kou et al., 2009; Lai et al., 1996; Lima et al., 2010; Marzouk et al., 2007; T. R. Naik et al., 1996; Panyakapo & Panyakapo, 2008; Rai et al., 2012; Ravindrarajah & Tuck, 1994; Ravindrarjah, 1999; Remadnia et al., 2009; Sabaa & Ravindrarajah, 1997; Saikia & de Brito, 2012, 2014; Silva et al., 2013, 2013; Tang et al., 2008; Wang & Meyer, 2012; Xu et al., 2012). The figures also demonstrate the compressive strength of concrete decreases more significantly when containing more uniformly shaped plastic aggregate than non-uniformly shaped plastic aggregate as well as when the plastic aggregate has a low elastic modulus (i.e. expanded polystyrene (EPS), and ethylene vinyl acetate (EVA)) rather than a high elastic modulus (i.e. polyethylene terephthalate (PET)). These existing studies made conclusions for the relatively low compressive strength of concrete containing plastic aggregates to five reasonings:

1. The elastic plastic modulus of the recycled plastic aggregates is lower than that of the natural fine or coarse aggregates.
2. The weak bond strength between the surface of the plastic aggregate and the cement paste.
3. The surface of the plastic aggregate is naturally hydrophobic causing a restrained cement hydration reaction at the surface of the plastic aggregate.
4. High air content and porosity of plastic aggregate.
5. Possible deterioration of PET aggregates exposed to the alkaline environment of the concrete pore fluid.

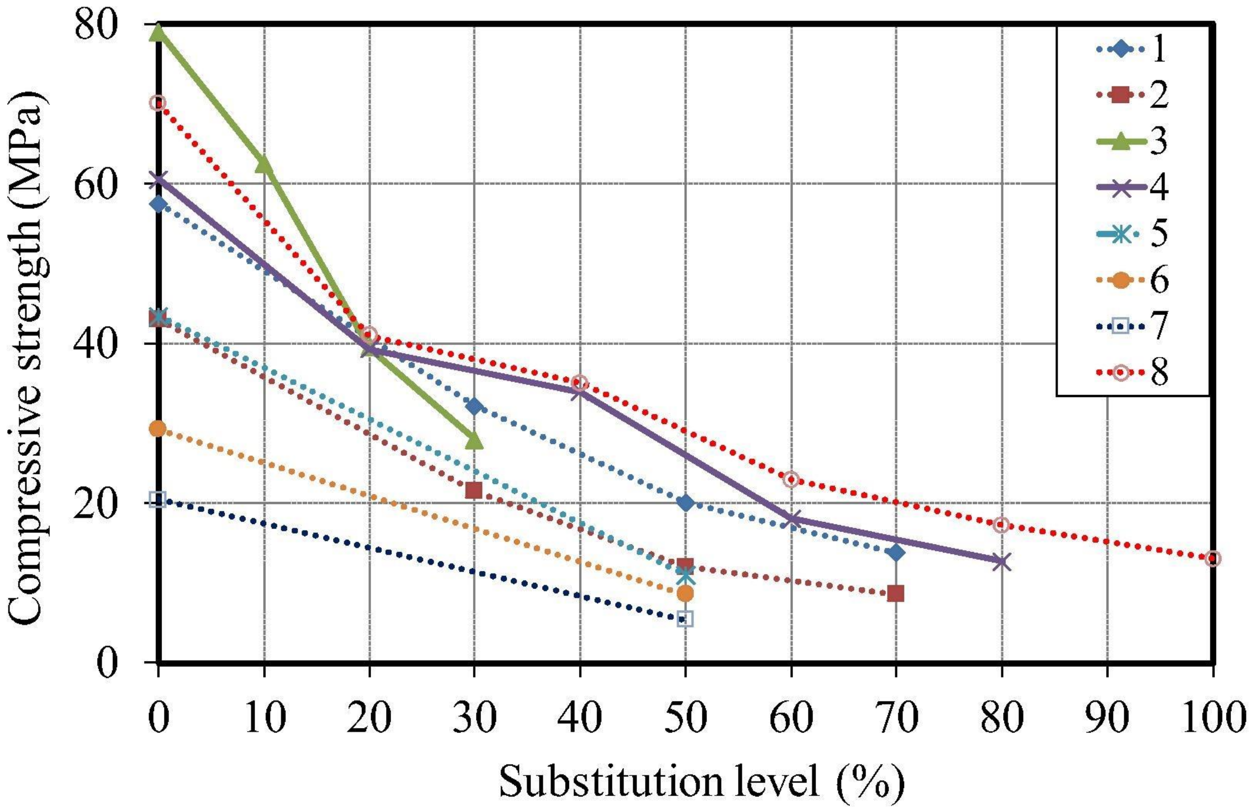

Figure 2-2 Compressive Strength versus Substitution Level

Figure 2-2 shows the variation of 28-day compressive strength of concrete with substitution level of plastic coarse aggregates: (1), (2): EPS (Sabaa & Ravindrarajah, 1997); (3): (Ravindrarjah, 1999); EPS (4): EPS (Tang et al., 2008); (5), (6), (7): EVA (Lima et al., 2010); and (8): PET (Akçaözoğlu & Ulu, 2014); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates]. (Gu & Ozbakkaloglu, 2016)

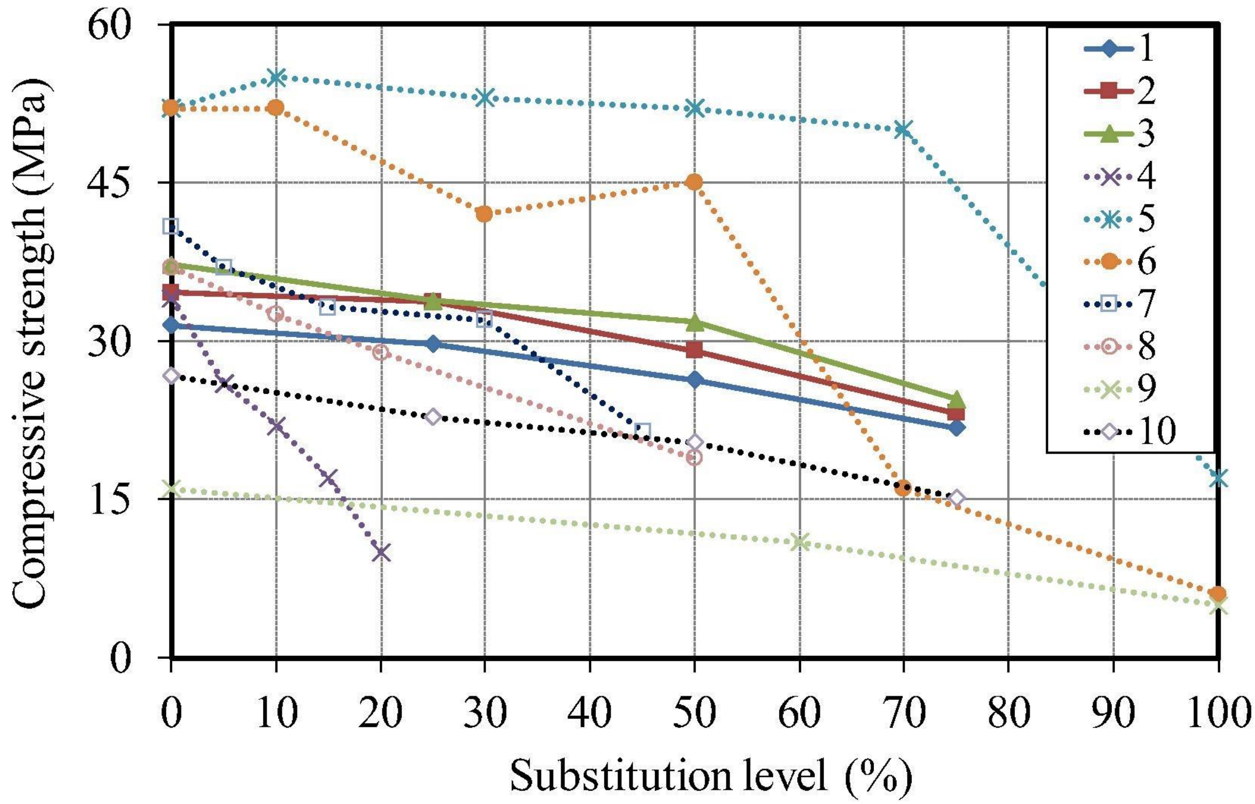

Figure 2-3 Compressive Strength versus Substitution Level

Figure 2-3 shows the variation of 28-day compressive strength of concrete with substitution level of plastic fine aggregates: (1), (2), (3): WPLA (Choi et al., 2005); (4): mixed plastic (Batayneh et al., 2007); (5), (6): PET aggregate mortar (Marzouk et al., 2007); (7): PVC (Kou et al., 2009); (8): HIPS aggregate mortar (Wang and Meyer, 2012); (9): EPS (Herki et al., 2013); and (10): PET (Juki et al., 2013); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates]. (Gu & Ozbakkaloglu, 2016)

ASTM C39 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* covers determination of compressive strength of cylindrical concrete specimens. This test method consists of apply a compressive axial load to a molded cylinder at a rate which is within the prescribed range until failure. The compressive strength is then found by dividing the ultimate load by the cross-sectional area of the specimen. The interpretation of these tests must be carefully evaluated as strength is not a fundamental or intrinsic property of concrete made by given materials. Values observed in these tests are dependent on the size and shape of the specimen as well as batching and mixing procedures, sampling, molding, and fabrication procedures, and the ages, temperature and moisture conditions during cuing.

2.3.3.2 Tensile Splitting Strength

Similar to the compressive strength, the splitting tensile strength of concrete with plastic aggregate is generally less than that of conventional concrete with the same *w/c*. Figure 2-4 shows the results from existing studies (Albano et al., 2009; Asokan et al., 2009; D. S. Babu et al., 2006; K. G. Babu & Babu, 2003; Chaudhary et al., 2014; Chen & Liu, 2004; Choi et al., 2005; Ferreira et al., 2012; Frigione, 2010; Galvão et al., 2011; Juki et al., 2013; Kan & Demirboğa, 2009; Kou et al., 2009; Lima et al., 2010; Ravindrarajah & Tuck, 1994; Saikia & de Brito, 2014; Silva et al., 2013; Tang et al., 2008; Wang & Meyer, 2012)on the effect of replacement plastic aggregate. The figure shows that the splitting tensile strength decreases with increasing amounts of plastic aggregate. More significant reductions are seen occur in concrete containing non-uniformly shaped plastic aggregates than that containing uniformly shaped plastic aggregates, opposite that of the compressive strength tests. Additionally, the splitting tensile strength of concrete containing plastic aggregate decreases when containing plastic with a low elastic modulus, similar to that of compressive strength results.

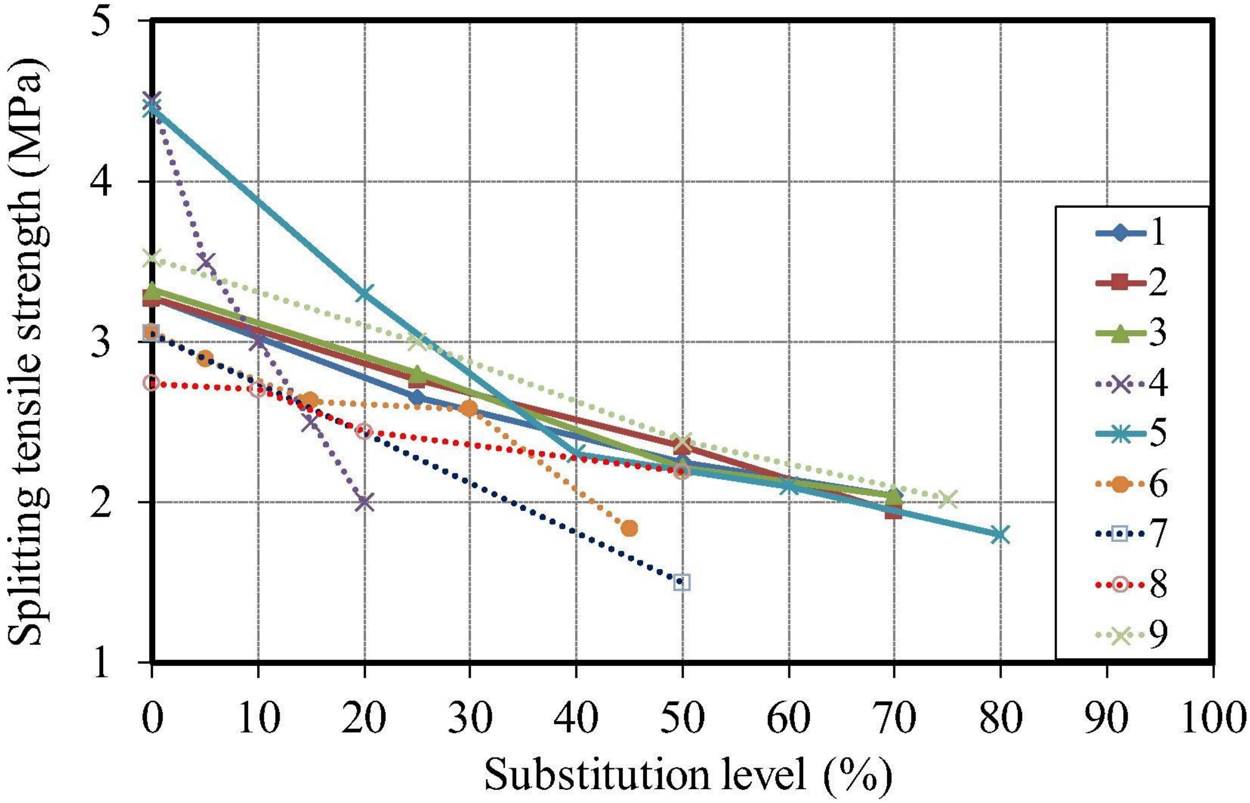

Figure 2-4 Tensile Splitting Strength versus Substitution Level

Figure 2-4 shows the variation of 28-day splitting tensile strength of concrete with substitution level of plastic aggregates: (1), (2), (3): WPLA fine aggregates (Choi et al., 2005); (4): mixed plastic fine aggregates (Batayneh et al., 2007); (5): EPS coarse aggregates (Tang et al., 2008); (6): PVC fine aggregates (Kou et al., 2009); (7): EVA coarse aggregates (Lima et al., 2010); (8): HIPS fine aggregates (mortar) (Wang & Meyer, 2012); and (9): PET fine aggregates (Juki et al., 2013); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates]. (Gu & Ozbakkaloglu, 2016)

ASTM C496 *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* covers the determination of the splitting tensile strength of cylindrical concrete specimens. This test method consists of applying a diametral compressive force along the length of a cylindrical concrete specimen at a prescribed rate until failure occurs. This method of loading induces tensile stresses on the plane containing the applied load and relatively high compressive stresses in the area immediately around the applied load. Tensile failure occurs instead of compressive failure because the areas of load application are in a state of triaxial compression, allowing them to withstand much higher compressive stresses than when in uniaxial compression. Thin plywood strips are used in the bearing area to distribute the load applied along the length of the cylinder. The ultimate load is divided by the appropriate geometrical factors to obtain the splitting tensile strength. Splitting tensile strength is generally lower than flexural strength (modulus of rupture) and higher than direct tensile strength (which is rarely tested). Splitting tensile strength is used to assess the shear capacity provided by the concrete and determine the development length of reinforcement in the design of structural lightweight concrete members.

2.3.3.3 Modulus of Rupture

The modulus of rupture in an indication of flexural strength. The flexural strength of concrete made with plastic aggregates depends on several parameters including: *w/c*, replacement rate of plastic aggregate, the type of waste plastic, the porosity of the plastic aggregates, and the transition zone characteristics. Figure 2-5 shows results from existing research (Akçaözoğlu et al., 2010; Akçaözoğlu & Ulu, 2014; Albano et al., 2009; Asokan et al., 2009; Frigione, 2010; Ge et al., 2013; Ismail & AL-Hashmi, 2008; Juki et al., 2013; Marzouk et al., 2007; Rai et al., 2012; Saikia & de Brito, 2014, 2014) on the effect of plastic aggregate on the modulus of rupture of concrete. As with compressive strength and tensile splitting strength, the modulus of rupture is generally lower with increased replacement rates of plastic aggregates when the same *w/c* is maintained. Additionally, the figure shows the decrease in modulus of rupture is more rapid when the shape of the plastic aggregates is less uniform or when the elastic modulus of the plastic decreases, similar to the effects on compression strength.

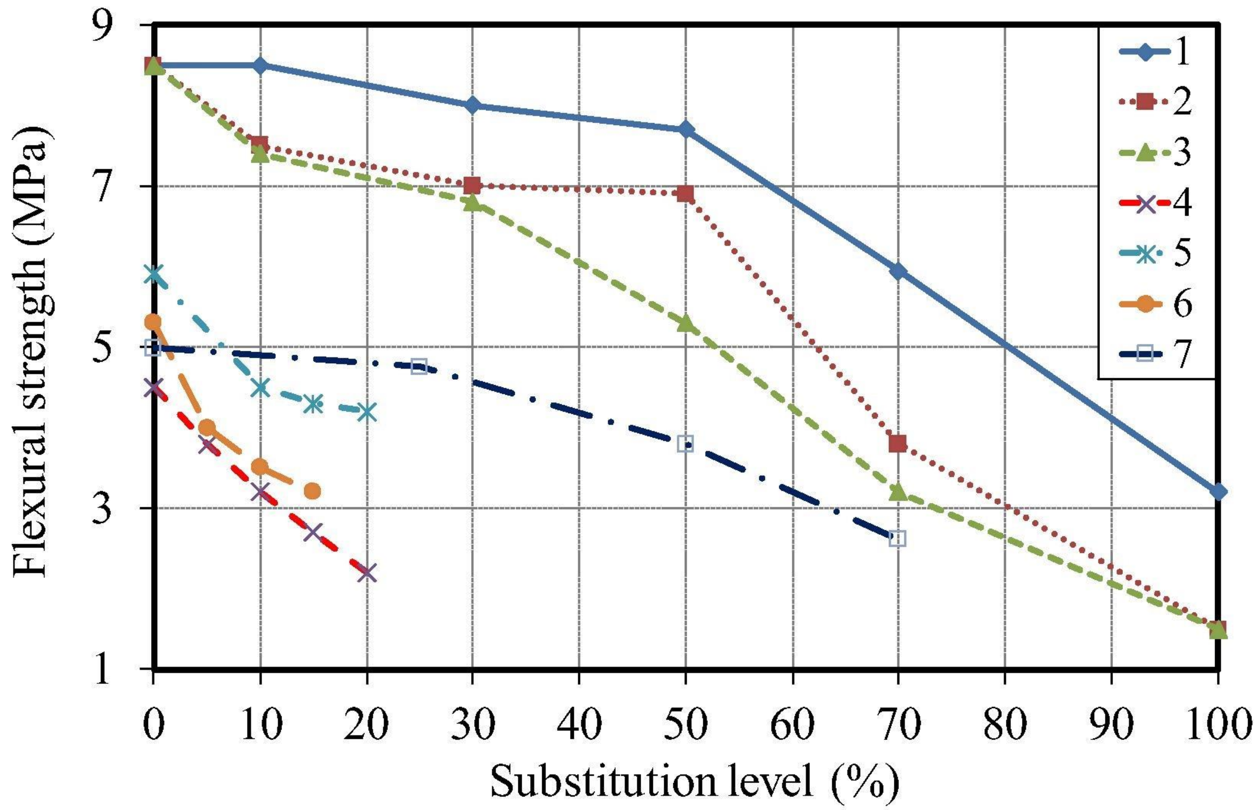

Figure 2-5 Flexural Strength versus Substitution Level

Figure 2-5 shows the variation of 28-day elastic modulus of concrete with substitution level of plastic aggregates (1), (2), (3): PET fine aggregates (mortar) (Marzouk et al., 2007); (4): mixed plastic fine aggregates (Batayneh et al., 2007); (5): mixed plastic (80% PET) (Ismail & AL-Hashmi, 2008); (6): mixed plastic fine aggregates (Rai et al., 2012), and (7): PET fine aggregates (Juki et al., 2013). (Gu & Ozbakkaloglu, 2016)

ASTM C78 *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)* covers the determination of flexural strength of concrete by use of a simple beam with third-point loading. This test method consists of applying a load, distributed to two points of contact, centered on a simple beam, between two pinned supports. The modulus of rupture shall be calculated by dividing the ultimate load by the appropriate beam dimensions. This test method is primarily used for testing concrete for use in slabs and pavements. If there are differences in specimen preparation, curing procedure, moisture condition at time of testing, and whether beams are molded or cut to size the strength determined will vary even if specimen size remains the same (*ASTM Standard C78 / C78M*, 2020).

2.3.4 Environmental Impact

However, there are other benefits to adding plastic wastes to concrete mixes. Figure 2-6, below shows a visualization of the material new lifespan that can be obtained by using recycled plastic in concrete. As shown, the usable lifespan of concrete is significantly longer than its unusable lifespan, whereas the usable lifespan of plastic is very short compared to its unusable lifespan. The third bar shows the implementation of recycled plastic in concrete. The plastic that has been rendered useless can have another life that does not involve remaining in a landfill or drifting in oceans and harming the environment (Sharma & Bansal, 2016).

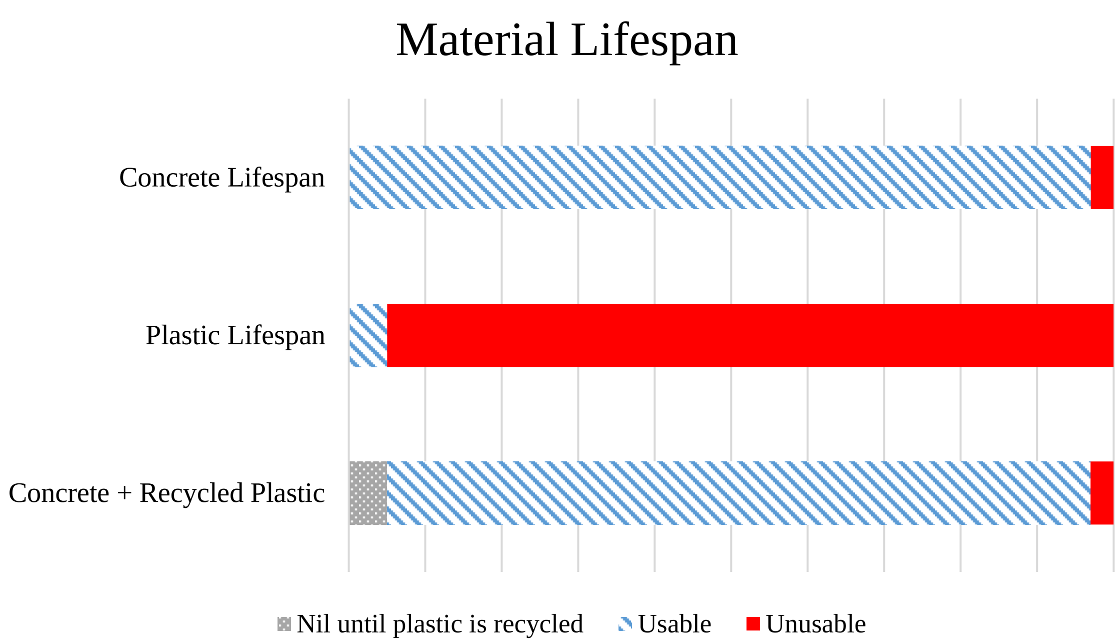

Figure 2-6 Material Lifespan

2.4 Application

The goal of these replacement aggregate material studies is to show the behavior of the concrete after the natural aggregates have been fully or partially replaced. In most studies, the concrete mixes containing recycled plastic aggregates decreased in mechanical properties (compressive strength, splitting tensile strength, modulus of rupture) (Manjunath, 2016), (Gravina et al., 2021), (Faraj et al., 2019). While this is unfortunate, it does not disqualify the concrete mixes from use. Designs using the alternative mixes will need to take into consideration the new properties.

The partial aggregate replacement amounts were determined from previous research combined and analyzed with different concrete mix designs and recycled plastic materials (Gu & Ozbakkaloglu, 2016). In these other studies a significant decrease in strength of the concrete would occur at 30% aggregate replacement. The other aggregate replacement percentages were determined to analyze trends and note where or if there was a significant decrease in strength. Fresh concrete properties, workability, density, and slump, were recorded as well as mechanical properties of compression strength, splitting tensile strength, and modulus of rupture were recorded.

The material used in this experiment is a commercially available product called Plazrok, it has been developed by Enviroplaz Plazrok is comprised of unsorted and unwashed resin codes 1-7, which includes plastic bags, multi laminate food packaging incorporating aluminum foil, plastic wrapping, and more, as well as colored glass and fly ash ("Plazrok," 2018). . These materials are put together in a proprietary blend called a masterbatch which is then used to form rock-like particles that can be used as a coarse aggregate replacement (Nick Walker, 2019).

Chapter 3 - Test Setup and Procedure

3.1 Mix Design

In order to study and collect the effects of increasing amounts of recycled aggregate replacement, Plazrok, four mixes of concrete were batched and cast into cylinders and prisms. The concrete mix design was based on a standard commercial interior mix used by Midwest Concrete Materials (MCM). The details of the mix design are documented in Appendix A - Concrete Mix Design. The mix design was adapted to batch five cubic yards of concrete. The concrete mixes batched were a control mix with only natural aggregates, and three mixes with natural coarse aggregate replaced with Plazrok at 15 percent, 30 percent, and 45 percent, by volume. The base mix used to determine quantities needed for each of the mixes is shown in Table 3.1. Table 3.2 indicates the quantities of the ingredients used for each mix design.

Table 3.1 Control Mix Design

Material Type	Description	Quantity		Specific Gravity	Volume (ft^3)
Cement	Type I/II Cement	564	lb.	3.15	2.87
Fine Aggregate	MCM KP Fine Aggregate	2024	lb.	2.63	12.34
Coarse Aggregate	MCM KP CA-4	1120	lb.	2.6	6.93
Water	Water	30.4	gal.	1	4.06
Replacement Aggregate	Plazrok by Enviroplaz	0	lb.	0.7	0
Admixtures	GcP Mid-Range Water Reducer	25	lq. oz.	-	-
		3962	**lb.**	**-**	**27.01**

Abbreviations are as follows: lb. (pound), gal. (gallon), lq. (liquid), oz. (ounce), ft^3 (cubic feet).

Table 3.2 Mix Designs

Mix	Cement *(pounds)*	Fine Agg. *(pounds)*	Coarse Agg. *(pounds)*	Water *(pounds)*	Plazrok *(pounds)*
Control	104.46	374.99	207.33	46.91	0.00
15% Replacement	104.46	374.99	176.96	46.91	8.41
30% Replacement	104.46	374.99	145.73	46.91	16.82
45% Replacement	104.46	374.99	114.50	46.91	25.22

3.2 Materials

Type I/II cement, locally obtained fine and coarse aggregates, and mid-range water reducer ADVA 140(M) were used in this testing. The aggregates and cement were from MCM and made available through the Civil Engineering Department at Kansas State University. The water-reducer was used to increase workability and slump. Plazrok was the material used as the recycled aggregate used as a replacement for the typical coarse aggregate. Figure 3-1 and Figure 3-2 show Plazrok replacement aggregate.

Figure 3-1 Plazrok in a Five-Gallon Bucket

Figure 3-2 Measured Plazrok

The bulk specific gravity and absorption capacity of the aggregates are shown in Table 3.3**Error! Reference source not found.**. This table shows that the specific gravity of the Plazrok is considerably lower than that of the traditional aggregates derived of sand and stone. The density of the concrete mixes will decrease as the percentage of replaced aggregate increase. The Plazrok also has a much higher absorption capacity. Table 3.4 displays the variation in size of the Plazrok, compared to the natural fine aggregate. This data was found using sieves and were thoroughly shaken to ensure all aggregates in the proper tray.

Table 3.3 Bulk Specific Gravity and Absorption Capacity

	Bulk Specific Gravity	*Absorption Capacity*
Coarse Aggregate	2.56	2.60
Fine Aggregate	2.58	0.85
Plazrok	0.70	~0.00

Table 3.4 Coarse Aggregate Size

Size of Aggregate	Plazrok	Natural Coarse Aggregate
Aggregates larger than 1/2"	24%	7%
Aggregates smaller than 1/16"	76%	79%
Aggregates larger than 1/16", smaller than 1/2"	0%	14%

3.3 Test Specimens

The mix designs result in a final volume of five cubic yards, used to fill three large (6" x 12") cylindrical molds for ASTM C496 testing, three small (4" x 8") cylindrical molds for ATSM C39 testing, and three prism molds (4" x 3" x 16") for ASTM C78 testing for each testing date, as well as, two redundant specimens for each size. The sizes for each test method were chosen because of the testing apparatuses and molds available. The sizes and shapes of each of the specimens were determined because of the testing apparatuses and molds available. The different sizes of cylinders is not a concern as the difference in tested strength can be assumed equal in a concrete mix of this specified strength (4000 psi) (Vandegrift & Schindler, 2006). Testing occurred at seven days, 14 days, 28 days, and 56 days. The large cylinders were tested for tensile splitting according to ASTM C496, 2020, "Standard Test Method for Flexural Strength of Concrete". The small cylinders are for compression testing according to ASTM C39, 2020, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". The prisms are for modulus of rupture testing according to ASTM C78, 2020, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)". The number of specimens for each mix design is indicated in Table 3.5.

Table 3.5 Testing Specimen Count

ASTM	*7 Days*	*14 Days*	*28 Days*	*56 Days*	*Redundant*	*Total*
C39	3	3	3	3	2	14
C496	3	3	3	3	2	14
C78	3	0	3	0	2	8

The most critical tests are the compression and tensile splitting tests as compressive strength is used to specify the concrete and splitting tensile strength is used in design of structural lightweight members to evaluate shear resistance and to determine the development length of reinforcement (*ASTM Standard C496 / C496M*, 2020). The modulus of rupture test is less critical in most applications, typically only used in specifications for slabs and pavements, (*ASTM Standard C78 / C78M*, 2020) as well as tilt-up panels, and the equipment available limited the amount of concrete able to be batched at a time.

3.4 Concrete Batching

Concrete was batched on four separate dates for each mix design. To prepare for each batching date the materials were measured out in five-gallon buckets before the time of batching. The concrete batches were mixed in a five cubic yard capacity standing mixer. The mixer was located indoors in a lab setup. The first materials to be added were water and cement, this so the mix started thin and then became thicker as more material was added to ensure the mixer could handle the load. The aggregates were then added into the mixer with the water reducer. The mixer ran for approximately 2 minutes to ensure a homogeneous mix. The mix was then assessed for workability and a slump test was performed. The mix design calls for a four-inch slump (Appendix A - Concrete Mix Design.

Each mold to make the cylinders and prisms was coated with a lubricant and wiped down to ease the removal from the molds. The molds were then filled according to each test's ASTM Standard (*ASTM Standard C39 / C39M*, 2020; *ASTM Standard C78 / C78M*, 2020; *ASTM Standard C496 / C496M*, 2020). The cylinders and prisms were placed in a moisture room, kept at greater than 99 percent relative humidity and 70 degrees Fahrenheit. The molds were removed 24 hours after batching and the specimens were returned to the moisture room until the appropriate testing date.

3.5 Strength Testing

Each test day began with removing the specimens from the moisture room and inspecting them for any imperfections. Imperfections include any noticeable spots of honeycomb or cylinders that did not form perfectly circular. Any specimens that had considerable imperfections were not tested. The specimens were then wiped off, marked with an identification, and weighed to determine the density of each mixture.

3.5.1 Compression Testing

The compression test (ASTM C39) was conducted using a Forney 250 Series Compression Machine with Automatic (VFD) Controls and Standard Frame (F), 250-kip capacity. The machine is set up to apply pressure at a rate of 35 ± 7 psi/sec on a 4" x 8" cylinder until the load decreases consistently and releases pressure when a significant crack is formed. The maximum load of the specimen and the type of fracture pattern according to Figure 3-3 was recorded (*ASTM Standard C39 / C39M*, 2020). Before each test the compression plates steel unbonded caps were wiped off and then the caps were placed on the cylinder and placed on the bottom bearing plate and adjusted to the center of the testing area. Three cylinders were tested and the results were recorded. Figure 3-4 and Figure 3-5, show a typical setup for the compression tests and one cylinder after cracking, respectively. Figure 3-5 shows broken cylinder with 30% replacement at seven-day curing, it had a type 3 break.

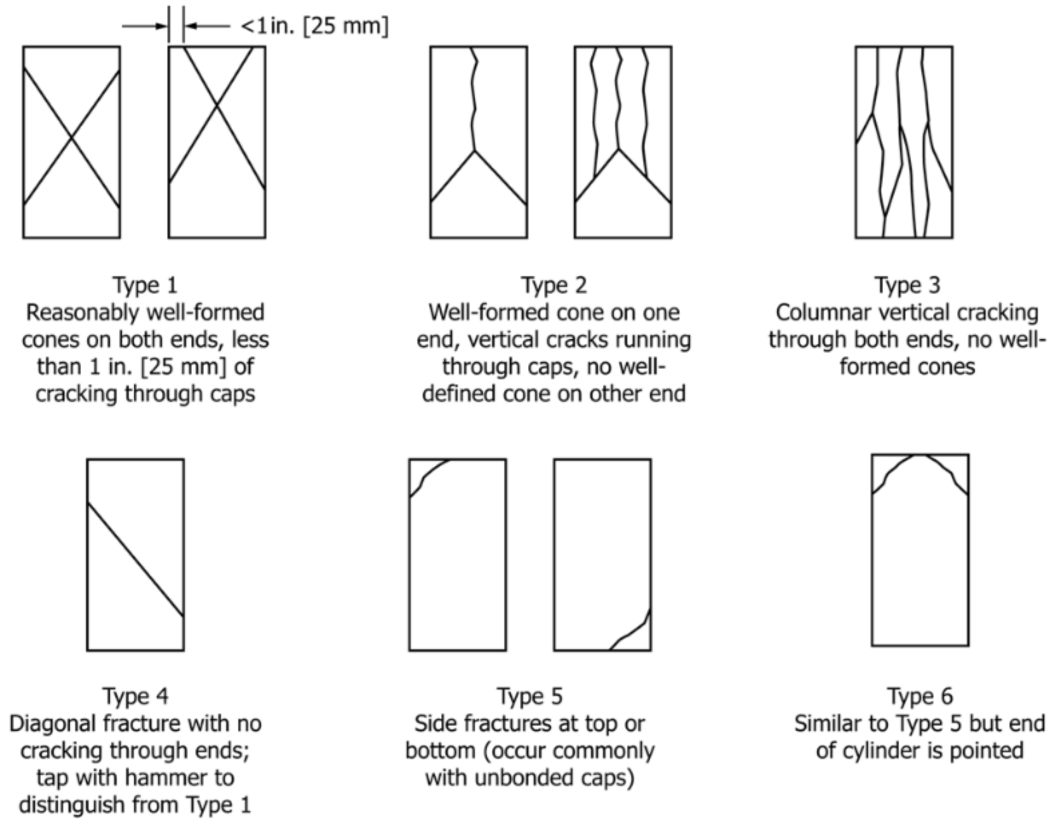

Figure 3-3 Fracture Type

Figure 3-4 Compression Test Setup

Figure 3-5 Cracked Cylinder - Compression Test

3.5.2 Tensile Splitting Testing

The tensile splitting tests (ASTM C496) were performed using a Baldwin Southwark Tate-Emery Universal Tensile/ Compression Tester, 350-kip capacity. Figure 3-6 shows a setup for the test. A large cylinder was placed on its side in an apparatus to hold the cylinder in place. Metal bars are placed on the top and the bottom of the cylinder with thin pieces of plywood to separate the cylinder from the metal bars. The containment apparatus was then centered under the compression plate. Pressure was to be applied at a rate in the range of 100 to 200 psi/min.

(pounds per square inch per minute) (*ASTM Standard C496 / C496M*, 2020). When the size of the cylinder is taken into consideration and minutes are converted to seconds for the units shown on the machine the pressure was applied at a range of 47 to 94 pounds per second. Pressure was released once the cylinder cracked. The cylinder was inspected to see the conditions of the crack and the test was repeated two more times. A cracked 30% replacement cylinder after seven-day testing is shown in Figure 3-7.

Figure 3-6 Tensile Splitting Test Setup

Figure 3-7 Cracked Cylinder - Tensile Splitting Test

3.5.3 Flexure Strength Testing

The Modulus of Rupture (ASTM C496) was performed on a Forney LA-270 Series Beam Tester Compression Machine with Manual Controls and Standard Frame (F), 30-kip capacity. The prisms were set on two pins 14 inches apart, equidistant from the center of the beam. The metal bearing device was then centered on the top of the beam, with two pins, four inches apart and a flat plate on top to uniformly apply loading from the Forney testing machine. The bearing device is shown in Figure 3-8 and Figure 3-9. The cracked prism in Figure 3-9 is a 15% replacement mix at seven-day strength testing. The compression plate was manually lowered until contact was made with the bearing plate. The load was then applied consistently at a rate of

125 to 175 psi/min. this equates to 25 to 35 lbs./sec. (pounds per second). The load was applied until breakage, the size and location of the crack was then recorded. The test was repeated on two more prisms.

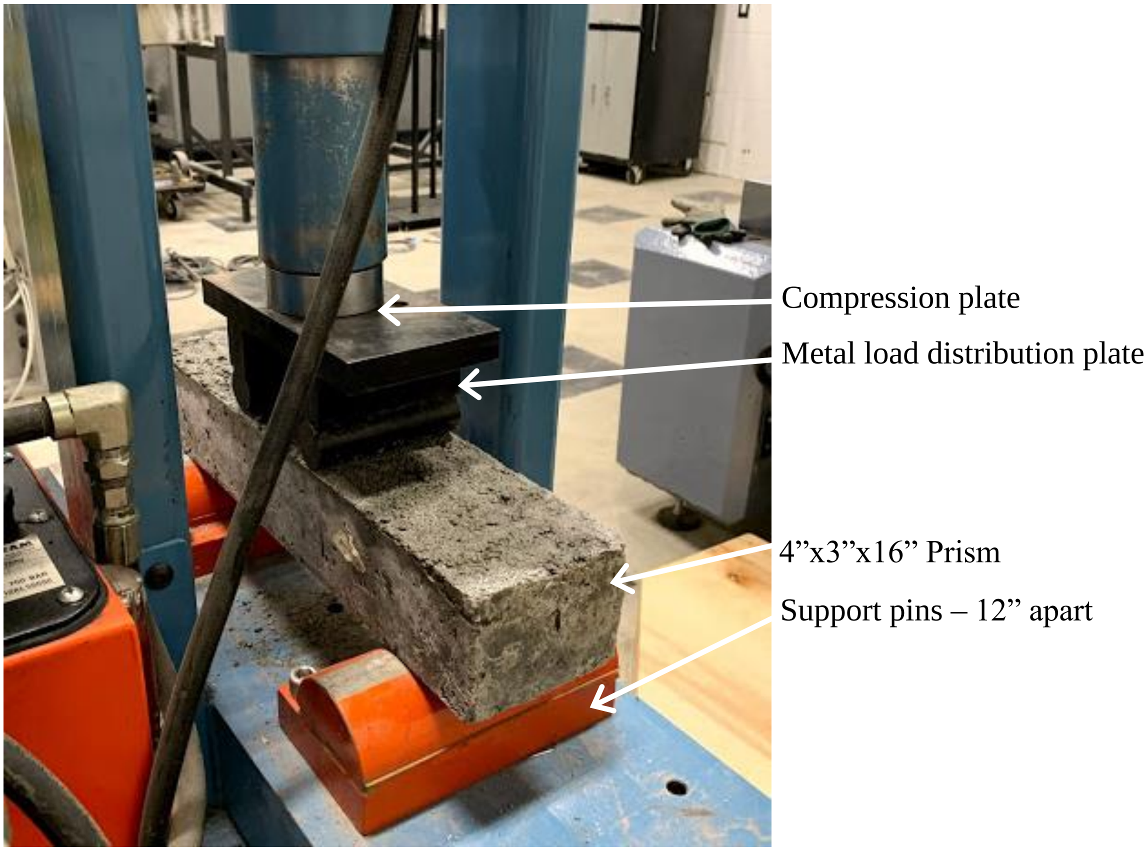

Figure 3-8 Modulus of Rupture Test Setup

Figure 3-9 Cracked Prism - Modulus of Rupture

Tests were repeated on specific days as previously described. All data was recorded according to ASTM standards. Results of the testing are discussed in the Chapter 4.

Chapter 4 - Test Results and Discussion

4.1 Fresh Concrete Properties

The properties of the four fresh concrete mixes are presented in Table 4.1. The water to cement ratio (*w/c*) and the predicted slump of the reference mix are 0.45 and 4.00 inches, respectively. No considerable change in workability of the concrete mixture occurred. Slump of the mixes increased as the percentage of natural aggregates was replaced. This is due to the lower absorption rate, additional free water, of the Plazrok compared to traditional aggregates. The density of the concrete mixes decreased consistently with the increase in replacement aggregate. Per the ACI (American Concrete Institute) 318-19, lightweight concrete ranges from 90 to 135 pounds per cubic foot. Therefore, the 45% replacement mix would qualify as lightweight concrete and so special design considerations must be taken if it is to be used for structural applications. The specific gravity of the Plazrok is 0.78 compared to 2.56 of the natural coarse aggregate.

Table 4.1 Fresh Concrete Properties

Fresh Concrete Properties				
Mix	*w/c*	*Slump (in.)*	*Density (lb/ft^3)*	*Percent Change in Density*
Control	0.45	4.00	146.16	0.00%
15%	0.45	4.25	142.11	-2.78%
30%	0.45	5.00	136.87	-6.36%
45%	0.45	5.00	132.73	-9.19%

Abbreviations are as follows: lb. (pound), in. (inch), w/c. (water to cement ratio).

4.2 Hardened Concrete Properties – Mechanical Properties

4.2.1 Compressive Strength

The compressive strength was found using Equation 4-1**Error! Reference source not found.** specified in ASTM C39.

$$f_{cm} = \frac{4P}{\pi D^2}$$ **Equation 4-1**

Where: f_{cm} = compressive strength, psi

P = load, lbf

D = average measured diameter, in.

The compressive strength of all concrete mixes followed a typical concrete strength development curve. The compressive strength of the concrete with increasing incorporation percentages of replacement aggregate decreased. This data (red for control mix, green for 15% replacement, blue for 30% replacement, and yellow for 45% replacement) is shown in Figure 4-1. The percent change between testing dates is shown in Table 4.2. It can be seen in the table that the percent increase from zero to seven days for the control mix is over double that of the 45% replacement mix. The 15% and 30% replacement mixes fall uniformly in between. The percent change from zero to seven days is significantly higher than any other part in the graph as the starting value is zero and also because of the expected development of strength of concrete. The percent change from seven to 14 days ranges from seven percent to 20%, with the control and 15% replacement mix having lower increases and the 30% and 45% replacement mixes having greater increases. The mixes continued to gain strength at 28- and 56-day testing: all mixes increased at similar rates (around 10%) except for the 45% mix from 28 to 56 days which only increased 3%. From this data, there does not seem to be a significant influence of incorporation of Plazrok on the strength development, other than the decrease in strength. The amount of loss in strength is fairly inversely proportional to the percentage of aggregate replacement, the percent of decrease in strength can be seen in Table 4.4.

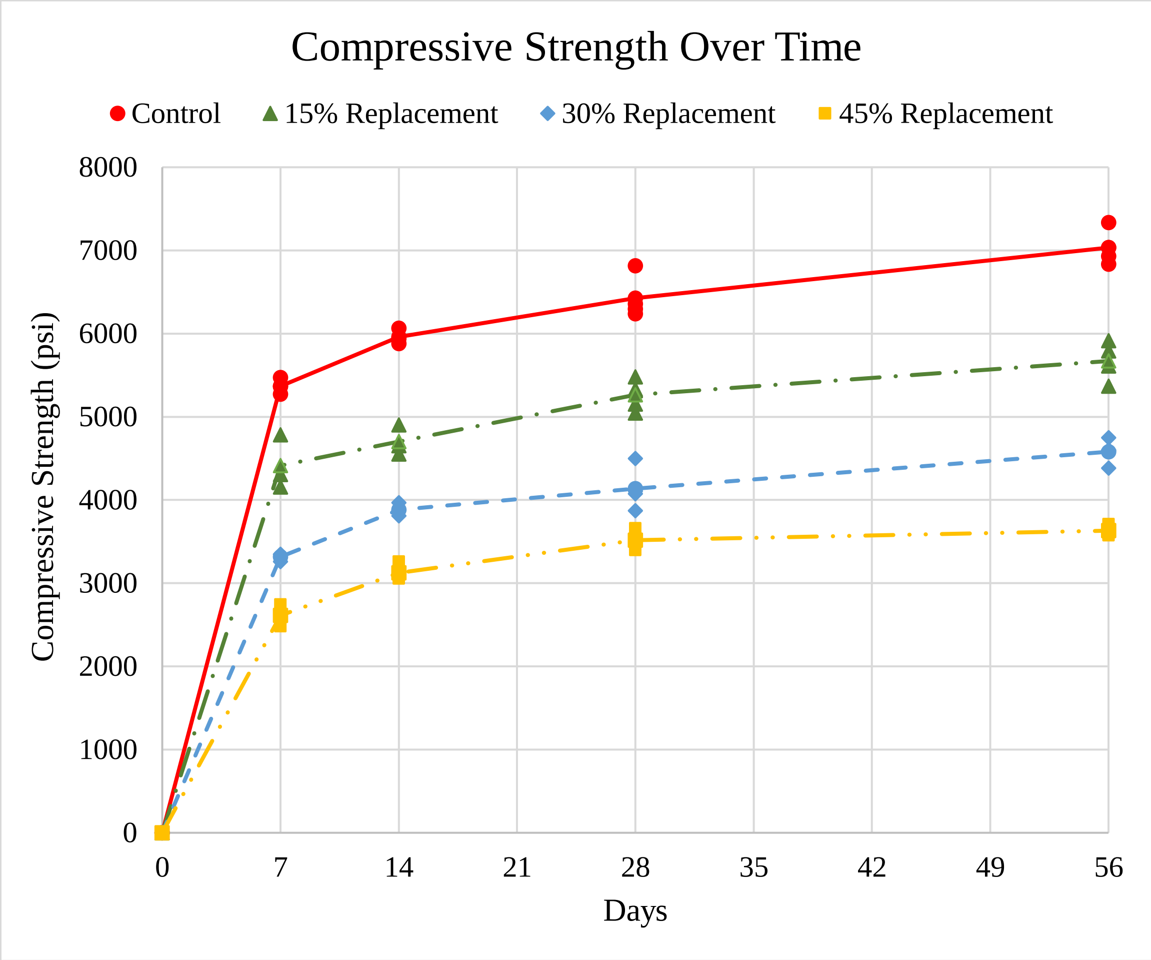

Figure 4-1 Compressive Strength Over Time

Table 4.2 Percent Change Between Test Dates

	0 to 7 days	*7 to 14 days*	*14 to 28 days*	*28 to 56 days*
Control	5369%	11%	8%	9%
15%	4415%	7%	12%	8%
30%	3316%	17%	7%	11%
45%	2614%	20%	13%	3%

Table 4.3 displays a full breakdown of the percent increase in compressive strength of the different concrete mixes from their strength at seven-day testing. The mixes with 30 and 45 percent replacement show much higher increases from the seven-day strength than the control and 15 percent mixes. When comparing the values of Table 4.3 to Table 4.2, it can be seen that the seven to 14-day increase is much higher for the 30% and 45% replacement mixes than the control and 15% mixes. This contributes to the higher overall strength increase values for the 30% and 45% mixes shown in Table 4.3.

Table 4.3 Average Compressive Strength and Percent Increase Over Time

		7 Days	**14 Days**	**28 Days**	**56 Days**
Control	Strength (psi)	5370	5960	6430	7030
	% Increase in strength from seven-day	0.00%	11.0%	19.7%	31.0%
15%	Strength (psi)	4420	4700	5260	5670
	% Increase in strength from seven-day	0.00%	6.5%	19.2%	28.4%
30%	Strength (psi)	3320	3880	4140	4580
	% Increase in strength from seven-day	0.00%	17.1%	24.8%	38.1%
45%	Strength (psi)	2620	3120	3520	3630
	% Increase in strength from seven-day	0.00%	19.5%	34.5%	38.9%

Table 4.4 displays similar information as Table 4.3 but the percent decrease in compressive strength of the different concrete mixes is from the control mix on each given

testing day and the average percent decrease shown by each mix design through all testing dates. Each mix design's percent decrease from control did not deviate greatly from the average shown on any testing date. This information can be useful for quick calculations and assumptions of concrete strength with different levels of replacement with Plazrok.

Equation 4-2 demonstrates a general, conservative approach to calculating the resulting compressive strength, given the strength of the control mixture at a specified time of curing and the percent of aggregate replacement with Plazrok incorporated. This equation only applies to the incorporation of Plazrok and not any recycled aggregate replacement.

Table 4.4 Compressive Strength and Percent Decrease from Control

	Control		15%		30%		45%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	5369	0.00%	4415	17.77%	3316	38.23%	2614	51.31%
14 Days	5960	0.00%	4703	21.10%	3884	34.84%	3125	47.58%
28 Days	6427	0.00%	5264	18.10%	4137	35.63%	3516	45.29%
56 Days	7034	0.00%	5670	19.38%	4581	34.88%	3631	48.37%
Average	**6197**	**0.00%**	**5013**	**19.09%**	**3979**	**35.89%**	**3222**	**48.14%**

$$f_{c\ replacement} = \frac{(1-(r+5))}{100} f_c$$ **Equation 4-2**

Where:

$f_{c\ replacement}$ = resulting compressive strength (psi)

f_c = tested compressive strength of control mix (psi)

r = percent of natural aggregate replaced with Plazrok (e.g. 15% = 15)

Figure 4-2 shows the average compressive strength of the concrete mixes tested in pounds per square inch. The trend lines all increase but at different slopes. This shows that the replacement aggregate mixes level off in their strength development curve earlier while the control mix continues to gain strength. The data also indicates a fairly steady decrease in strength as the amount of replacement aggregate increases. The values for the amount of decrease in strength are displayed in Table 4.4 The average compressive strength at 28 days decreases from the control mix strength by approximately 19% at 15% replacement aggregate, 36% at 30% replacement aggregate, and 46% at 45% replacement aggregate.

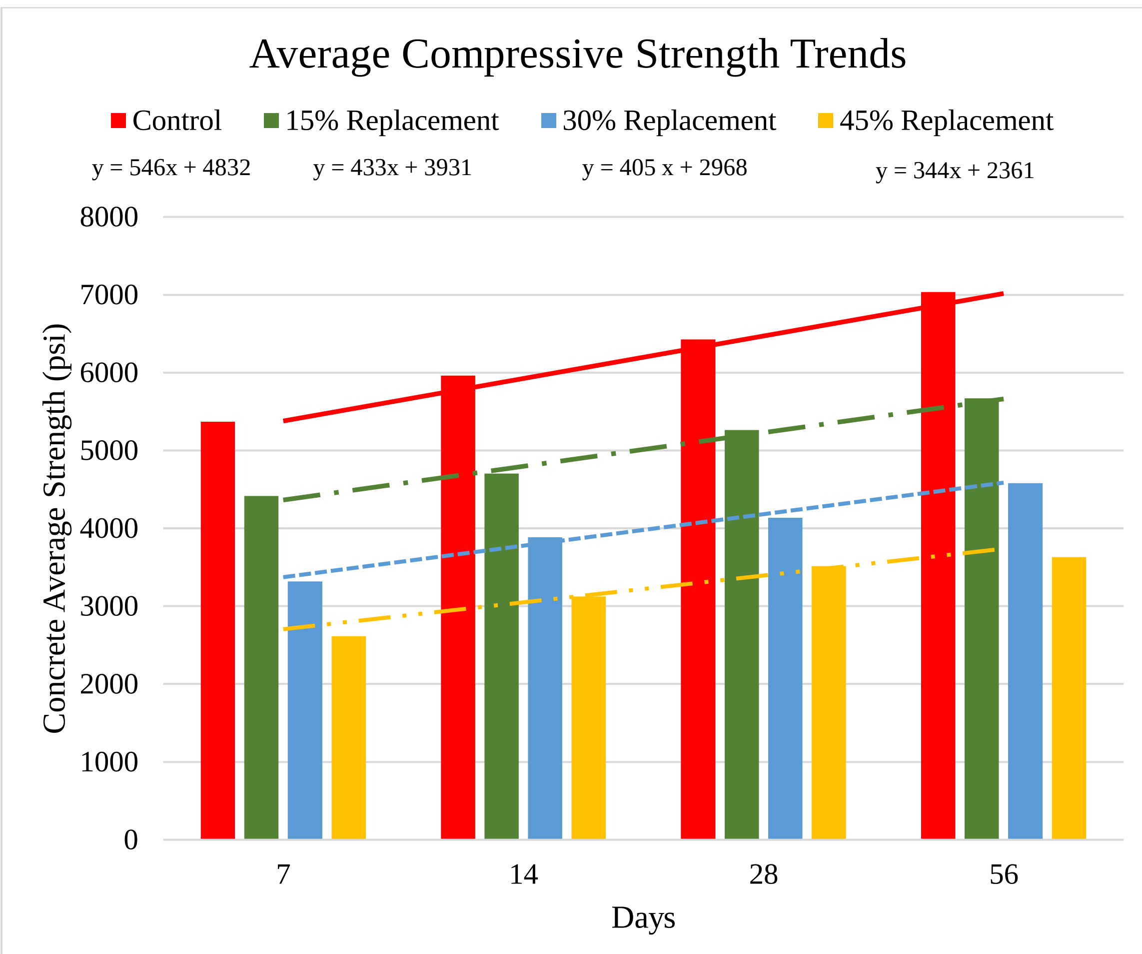

Figure 4-2 Average Compressive Strength Trends

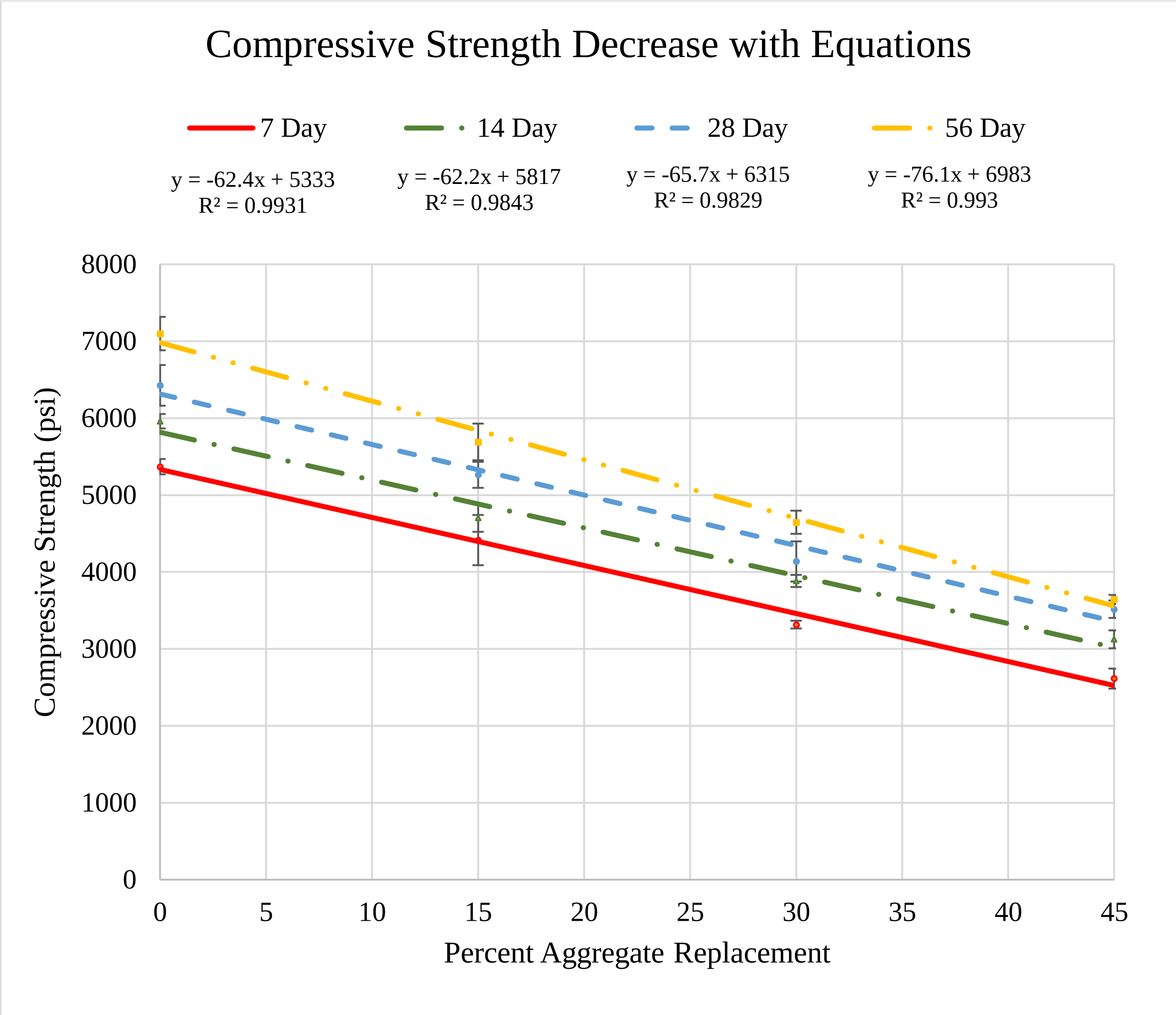

Figure 4-3 Compressive Strength Decrease with Equations

The trend of decrease in concrete compressive strength is linear. This allows for equations to be formed to best fit the decrease in strength. Figure 4-3 shows the trend lines of the averages of the concrete strengths for each testing day along with the error bars. The linear trendlines follow the averages of each testing date as the percent of replacement aggregate increased. Equations were formed based on these trendlines, these are much more specific than the

Equation 4-2, given earlier. The equations can be used with this concrete mix to predict the resulting strength of the mix with replaced aggregate. Equation 4-4, Equation 4-5, Equation 4-6, and Equation 4-6 show how to equate the resulting compressive strength at seven days, 14 days, 28 days and 56 days, respectively.

$$f_{c7} = -62.4r + 5333$$ **Equation 4-3**

$$f_{c14} = -62.2r + 5817$$ **Equation 4-4**

$$f_{c28} = -65.7r + 6315$$ **Equation 4-5**

$$f_{c56} = -76.1r + 6983$$ **Equation 4-6**

Where:

f_{cx} = resulting compressive strength (psi)

r = percent of natural aggregate replaced with Plazrok (e.g. 15% = 15)

4.2.2 Tensile Splitting Strength

The tensile splitting strength is determinate on the ability of the concrete to bind together. Often the reason for splitting tensile failure in concrete is the aggregates do not have a strong enough bond to the cementitious mixture (Saikia & de Brito, 2014). Equation 4-7 is used to calculate the tensile splitting strength.

$$T = \frac{2P}{\pi dl}$$ **Equation 4-7**

Where:

T = splitting tensile strength, psi

P = applied load indicated by testing machine, lbf

l = length, in.

d = diameter, in.

Figure 4-4 depicts the results of testing for splitting tensile tests. Each data point represents the strength of a single cylinder and the trend line follows the average strength at each day for each mix design. The lack of consistent trends is in part due to the method in which tensile splitting tests are performed and the fact that concrete is brittle in tension. The cylinders will split very suddenly and the machine used for this test is a manually operated hydraulic press that does not always deliver consistent loading. Due to these issues, the results of the testing show more variance in the expected trend of increase in strength over time than the compression tests.

It is possible the breaks occurred at specific points where the aggregate was not fully bonded with the cement paste or at a point where the aggregates may have not been distributed as well. More examination should be done on these possible reasonings.

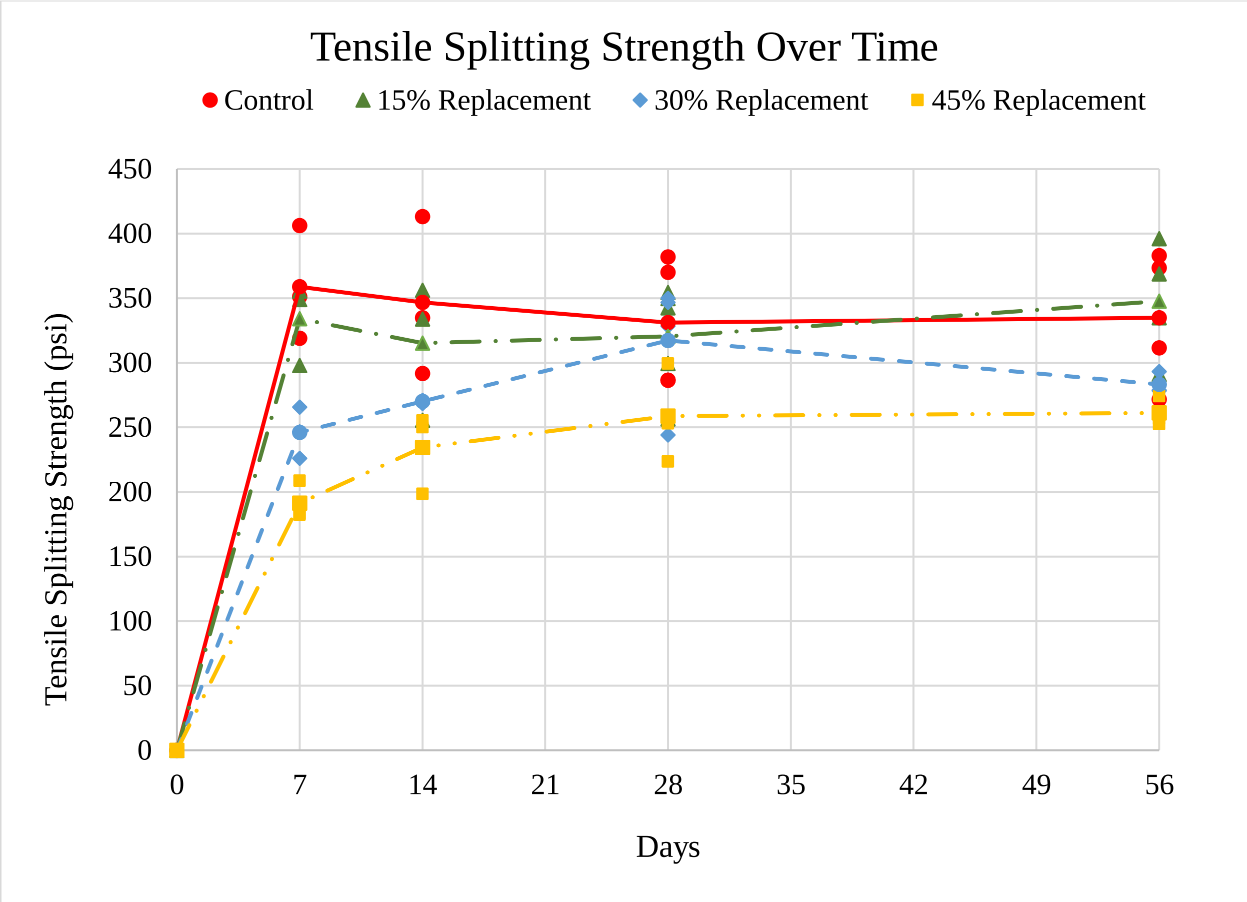

Figure 4-4 Tensile Splitting Strength over Time

Figure 4-5 illustrates the average tensile splitting strength average for each mix and the trendline of the increase or decrease over time. The trendline for the 15%, 30%, and 45% replacement mixes all increase as time increases although at varying rates which can be seen in the figure. The equations for each trendline are shown in the figure and denote the slope. The trendline for the control mix decreases as time increases. This is likely due to the same reasons as the variance shown in Figure 4-4. These values and trends are shown numerically in Table 4.5 and Table 4.6.

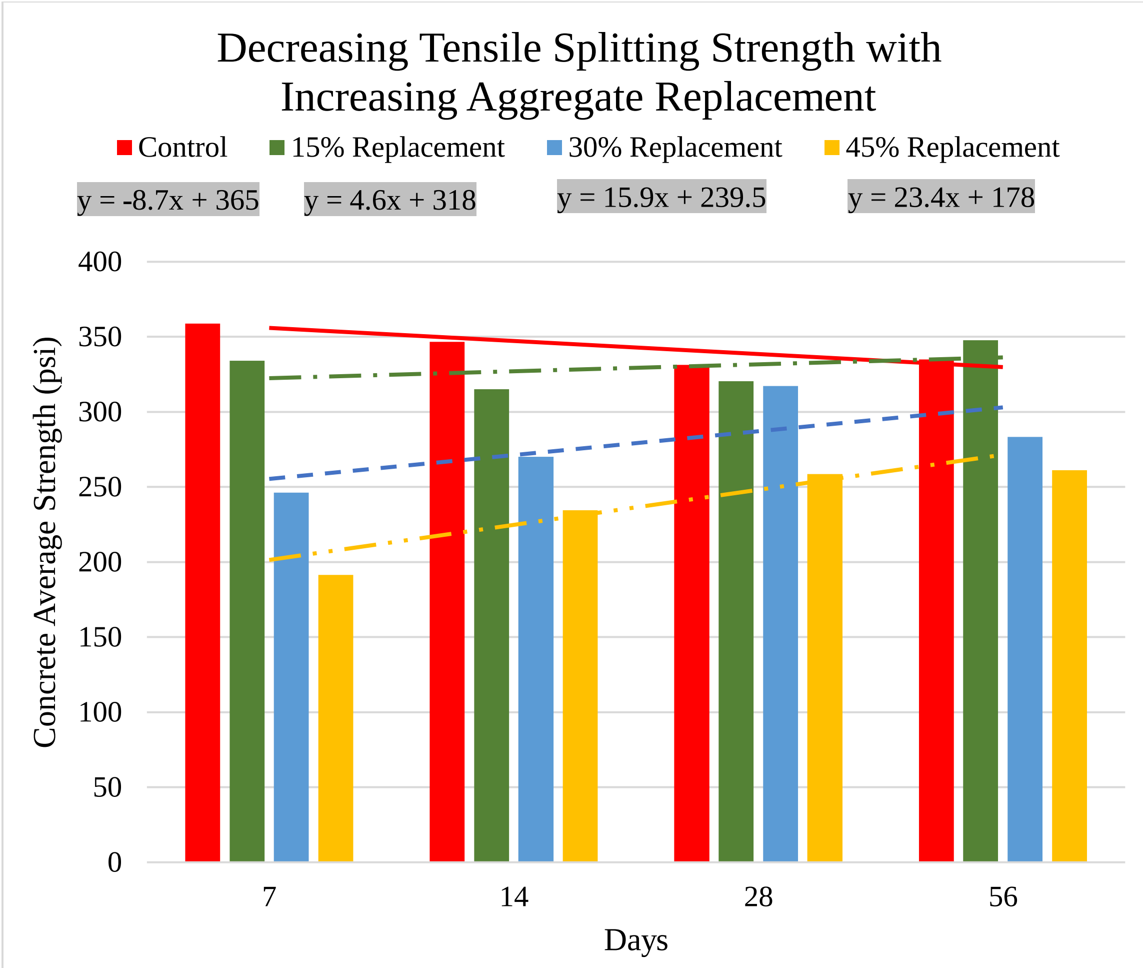

Figure 4-5 Tensile Splitting Strength Averages

The tensile splitting strength average for each test and the percent decrease in strength of each mix from the control mix after the same amount of time passed is given in Table 4.5. The percent decrease from is inconsistent for each mix design. The 15% mix decreased the least with 6.9%, 9.1%, 3.2%, and -3.8% decreases at seven, 14, 28, and 56 days, respectively. The 30% mix decreased the least with 31.4 %, 22.1%, 4.2%, and 15.4% decreases at seven, 14, 28, and 56 days, respectively. The 45% mix decreased the least with 46.7%, 32.3%, 21.9%, and 22.0% decreases at seven, 14, 28, and 56 days, respectively. This is partially due to the control mix decreasing in strength over time.

Table 4.5 Tensile Splitting Strength and Percent Decrease

	Control		15%		30%		45%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	360	0.00%	335	6.9%	245	31.4%	190	46.7%
14 Days	345	0.00%	315	9.1%	270	22.1%	235	32.3%
28 Days	330	0.00%	320	3.2%	315	4.2%	260	21.9%
56 Days	335	0.00%	350	-3.8%	285	15.4%	260	22.0%

Because of the behavior of the control mix, Table 4.6 was developed. Table 4.6 shows similar information to Table 4.5 but the percent change shown is of each mix design in comparison to its strength at 7 days. This table numerically shows the disparities in the trends of the strength development. The control mix decreased in strength from the seven-day strength at 14, 28, and 56 days at -3.39%, -7.68%, and -6.65%, respectively. The 15% mix decreased at 14 and 28 days at -5.65% and -4.06% respectively but then increased again at 56 days at 4.08%. The 30% mix increased at 14, 28, and 56 days at 9.71%, 28.91%, and 15.11%, respectively and had a much higher increase at 28 days than either of the other days. The 45% mix was the only mix that continuously increased: a large increase from the seven-day strength to 14-day occurred (22.58%) and then continued to increase at a lower rate at 28 and 56 days, 35.20% and 36.49%, respectively.

Table 4.6 Average Tensile Strength and Percent Increase Over Time

		7 Days	14 Days	28 Days	56 Days
Control	Strength (psi)	358.8	346.6	331.2	334.9
	% Increase in strength from seven-day	0.00%	-3.39%	-7.68%	-6.65%
15%	Strength (psi)	334.1	315.2	320.5	347.7
	% Increase in strength from seven-day	0.00%	-5.65%	-4.06%	4.08%
30%	Strength (psi)	246.1	270.0	317.3	283.3
	% Increase in strength from seven-day	0.00%	9.71%	28.91%	15.11%
45%	Strength (psi)	191.3	234.5	258.7	261.2
	% Increase in strength from seven-day	0.00%	22.58%	35.20%	36.49%

4.2.3 Modulus of Rupture

Equation 4-8 is used to calculate the modulus of rupture. The modulus of rupture was tested only at seven- and 28-day strengths. Figure 4-6 shows each of the strength results with a trendline following the average of each mix. The mixes increased quickly in strength, as shown by the results of the seven day but did not continue to increase, as the results of the 28-day strength show. Each of the plotted points in Figure 4-6 show there was little variance within each grouping of prisms. The control mix and 15% mix had very similar strengths at seven-day strength (279 psi and 275 psi, respectively). As did the 30% and 45% mixes (193 psi and 182 psi, respectively). The 28-day strength behavior is different and the strengths for control, 15%, 30%, and 45% all change at different rates. These values are shown numerically in Table 4.7.

$$R = \frac{PL}{bd^2}$$ **Equation 4-8**

Where:

R = modulus of rupture, psi

P	=	applied load indicated by the testing machine, lbf
L	=	span length, in.
b	=	average width of specimen at the fracture, in
d	=	average depth of specimen at the fracture, in

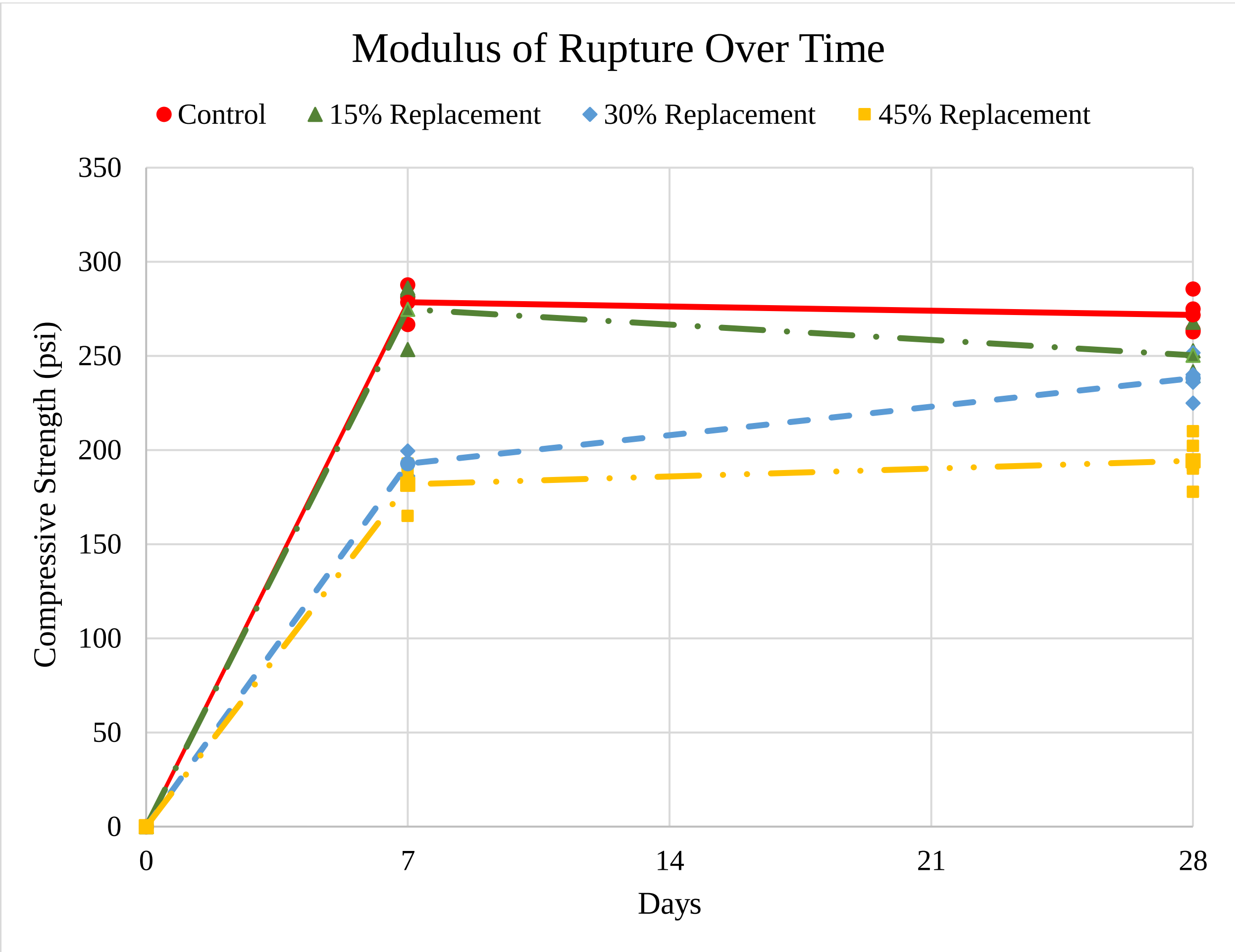

Figure 4-6 Modulus of Rupture Over Time

Figure 4-7 also shows the averages of each mix on each testing date with trendlines connecting the measured amounts. It shows that the only mix designs that increased in strength over the 21 additional days were the 30% and 45% replacement mixes. The control mix and 15% replacement mixes both decreased as time increased.

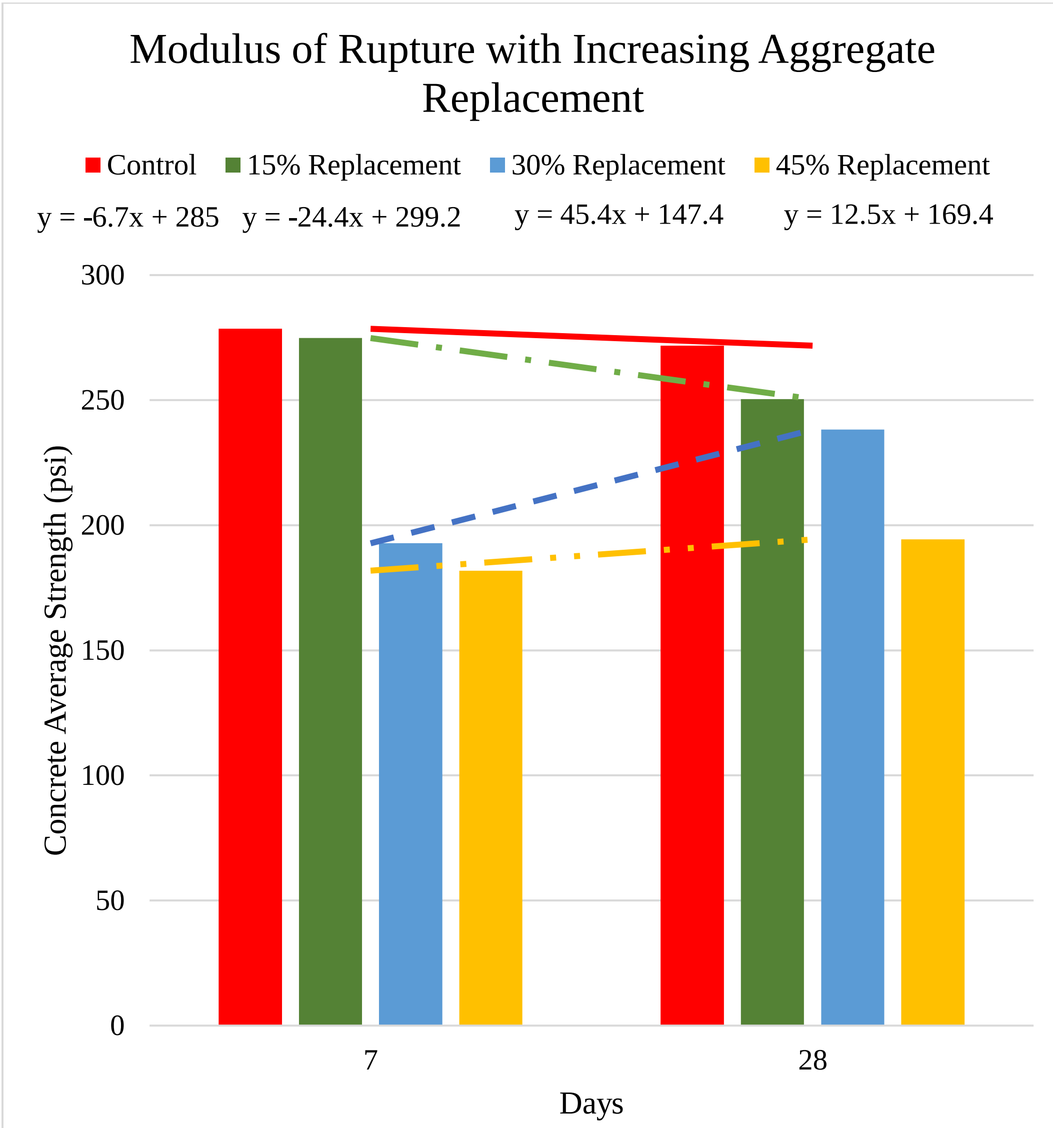

Figure 4-7 Average Tensile Splitting Strength Trends

Table 4.7 shows the averages flexure strength for each mix at the seven and 28-day testing dates and the percent strength decrease from the control mix. The 15% mix only loses 1.33% of its strength from control at seven days but loses 7.86% strength at 28 days. The 30%

mix has a slower development of strength and has a 30.78% decrease at seven days but only a 12.86% decrease at 28 days. The 45% mix followed similar trend as the control mix but had much less strength, with 34.71% and 28.5% decrease in strength at seven and 28-days, respectively.

Table 4.7 Average Modulus of Rupture and Decrease from Control

	Control		15%		30%		45%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	280	0.00%	275	1.33%	195	30.78%	180	34.71%
28 Days	270	0.00%	250	7.86%	240	12.36%	195	28.50%

4.2.4 Split Tensile Strength Versus Compressive Strength

Equations model the expected relationship between split tensile strength and compressive strength of new concrete. Equation 4-9 and Equation 4-10 show a relationship as described in Chapter 24 of the ACI building code. Equation 4-10 shows the allowed upper bound relationship.

$$f_{st} = 6f'_c{}^{0.5}$$ **Equation 4-9**

$$f_{st} = 7.5f'_c{}^{0.5}$$ **Equation 4-10**

$$f_{st} = 3.8f'_c{}^{0.52}$$ **Equation 4-11**

Where:

f_c = Compressive strength (psi)

f_{st} = Tensile splitting strength (psi)

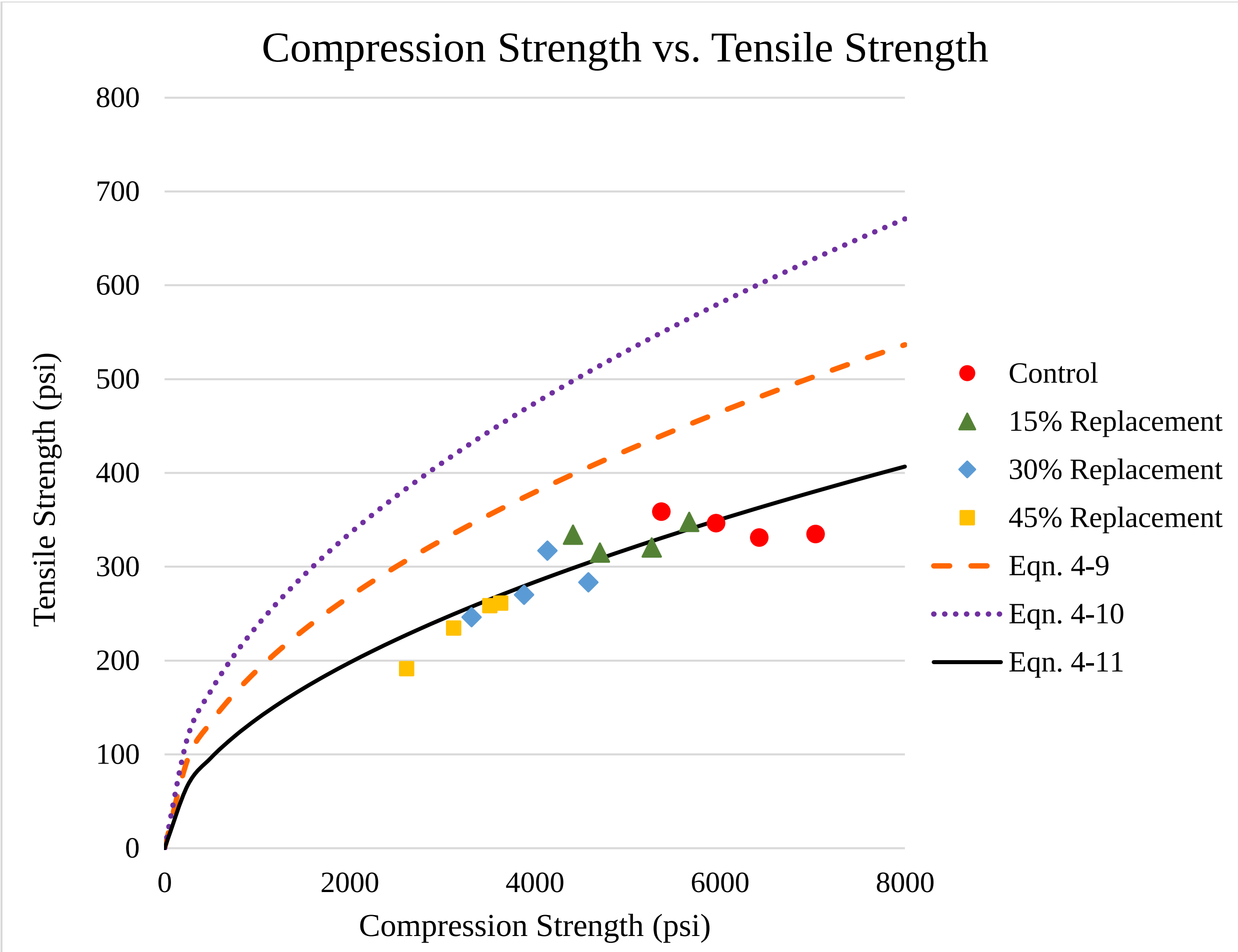

Figure 4-8 Compression Strength Versus Tensile Splitting Strength

Figure 4-8 shows Equation 4-9 and Equation 4-10 plotted against the averages of each testing date for each mix design. Both equations overestimate the splitting tensile strength in comparison to the compressive strength. Other research has shown that these equations do not always agree with test results and other relationship equations have been proposed (Jaber et al., 2018). The data points in this study fall below the expected splitting tensile strength but this is acceptable as the equations show upper limits. Equation 4-11 more accurately predicts the splitting tensile strength from the compressive strength for the mix designs in this experiment. The equation was formed as a best fit line by adjusting the coefficient and exponent so that a accurate line could be formed. The general trend of tensile splitting strength to compressive strength was consistent through all mix designs. This line shows that the there is little to no effect of the addition of Plazrok to the mix on the relationship between the tensile and compressive strengths of the mix as all of the data points fall close to the best fit line.

4.2.5 Modulus of Rupture Versus Compressive Strength

The modulus of rupture can be calculated using Equation 4-12, this equation is from ACI 318-19 equation 19.2.3.1. The value for λ shall be taken as 1.0 for normal weight concrete (ACI Committee 318, 2019).

$$f_r = 7.5f'_c{}^{0.5}$$ **Equation 4-12**

$$f_r = 3.5f'_c{}^{0.5}$$ **Equation 4-13**

Where:

f_r	=	Modulus of Rupture (psi)
λ	=	Factor for lightweight concrete, (equal to 1.0)
f_c	=	Compressive strength (psi)

Figure 4-9 shows the relationship between the compressive strength and the modulus of rupture testing strengths. Each node is the averages of the 28-day strength for either test. The modulus of rupture test was performed at seven and 28 days, but the full compressive strength is not met by the seven-day mark. Including that date would not show an accurate relationship between the compressive strength and modulus of rupture. Equation 4-12 over estimates the modulus of rupture strength in comparison to the compressive strength of the test specimens.

Equation 4-13 was developed to better demonstrate the relationship of the modulus of rupture to the compressive strength of the mixes in this experiment.

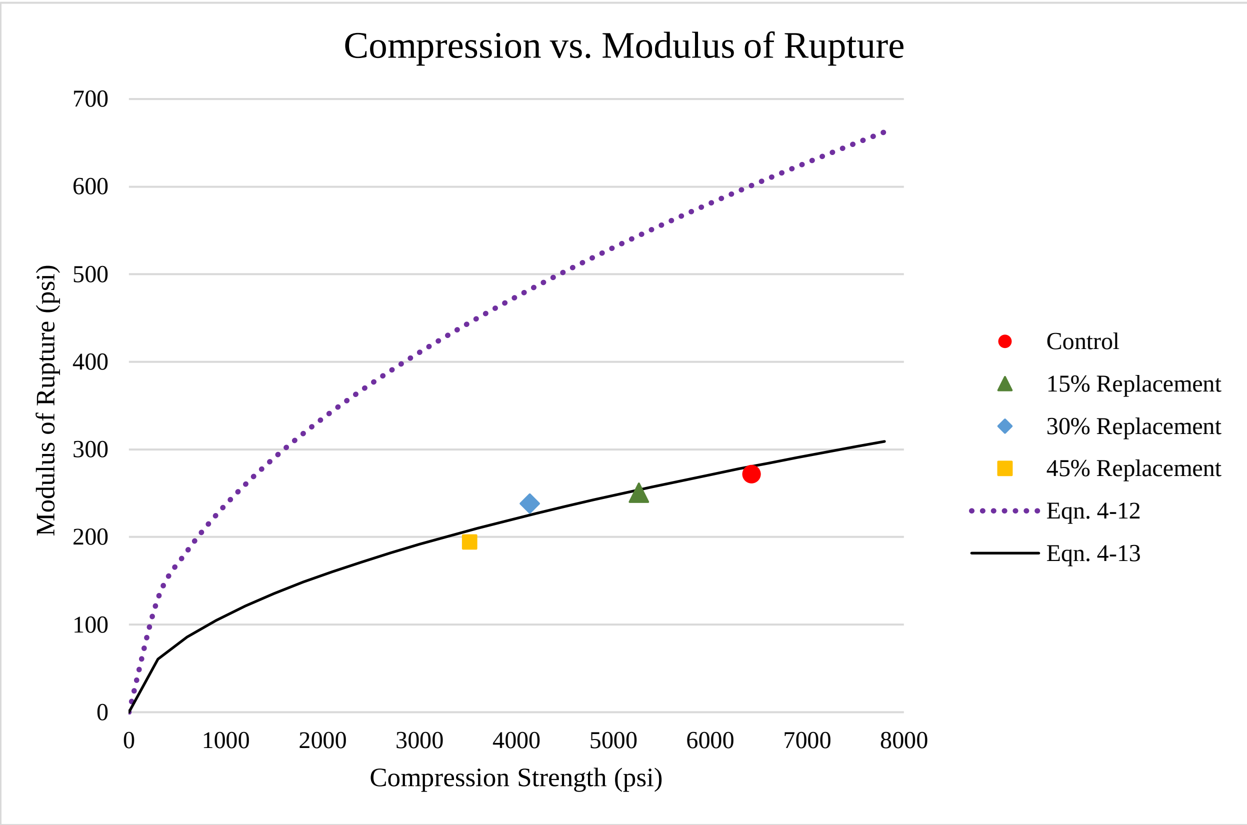

Figure 4-9 Compressive Strength Versus Modulus of Rupture

4.2.6 Distribution and Breakage

Due to the low specific gravity of the Plazrok, there was a concern that it would not distribute evenly within the cylinders and prisms. Samples were taken from the large cylinders used in the splitting tensile test and examined for the distribution of Plazrok. Equation 4-10 and Figure 4-11 shows the distribution of the Plazrok in the large cylinders. Each visible bit of Plazrok is circled and the top of the cylinders are at the top of the figures. The distribution of the

Plazrok in the cut cylinders is well dispersed throughout the cylinder. There are no evident clusters of Plazrok and no evidence that the Plazrok settled nearer the top of the cylinder than anywhere else in the height. This shows that the low specific gravity of the Plazrok did not have any bearing on the distribution of the aggregates in the cylinders.

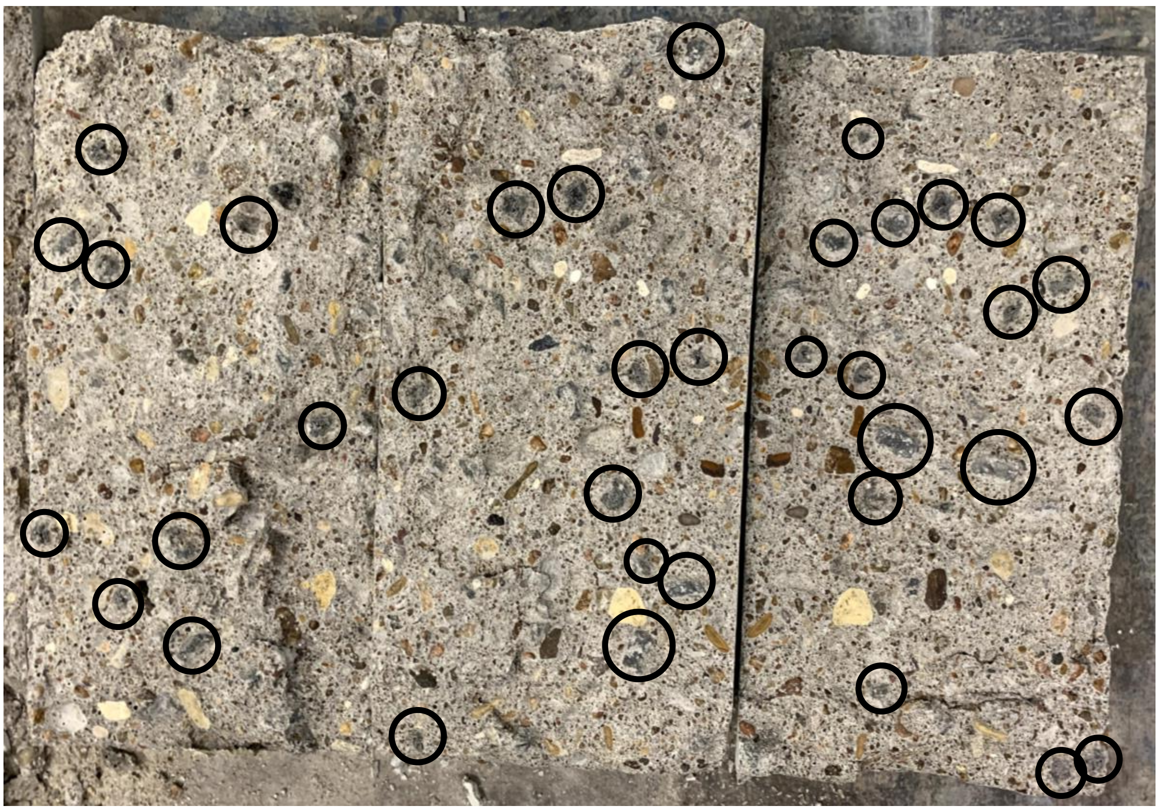

Figure 4-10 Plazrok Distribution

Figure 4-11 Plazrok Distribution

4.3 Results Comparison

As beforementioned, there have been many different applications of incorporating plastic waste into concrete. While all studies discussed lost strength as more recycled plastic aggregate was incorporated, there was differences in the rate of decrease. The differences are due to the different concrete base mixes, different types of plastic, different shapes and sizes of the replacement aggregates, various treatments applied to the aggregates, as well as the plastic being used as a fiber, fine aggregate, or coarse aggregate (Gu & Ozbakkaloglu, 2016). It is important to compare the different application methods to access the strengths and weaknesses of each mix.

The results of this study are compared to the results of (Manjunath, 2016). This study uses E-plastics, such as cathode tubes (used in TVs, computer monitors, video cameras, etc.), printed circuit boards, chips, plastics from printers, keyboards, monitors, etc., and computer wires. These materials are especially difficult to recycle and can produce toxins. The study used replacement rates of coarse aggregates at 0%, 10%, 20%, and 30% and tested compression strength, splitting tensile strength and flexural strength. The results from (Manjunath, 2016) are presented in Table 4.8, Table 4.10, and Table 4.12.

There are differences in the way these studies were conducted as Manjunath used the Indian Standard method of mix design and this study used American Standard for Testing and Materials (ASTM) C39.

Table 4.8 Compressive Strength and Decrease from Control (Manjunath, 2016)

	Control		10%		20%		30%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	5221.4	0.00%	4812.4	7.8%	2886.3	44.7%	2377.2	54.5%
14 Days	6499.2	0.00%	5982.8	7.9%	2603.4	59.9%	2760.1	57.5%
28 Days	6842.9	0.00%	6391.8	6.6%	3581.0	47.7%	3212.6	53.1%
Average	**6187.8**	**0.00%**	**5729.0**	**7.5%**	**3023.6**	**50.8%**	**2783.3**	**55.0%**

Results have been converted from N/mm^2 (Newton per square millimeter), to psi (pounds per square inch)

Table 4.9 Compressive Strength and Decrease from Control (Plazrok)

	Control	15%	30%	45%

Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	5369	0.00%	4415	17.8%	3316	38.2%	2614	51.3%
14 Days	5960	0.00%	4703	21.1%	3884	34.8%	3125	47.6%
28 Days	6427	0.00%	5264	18.1%	4137	35.6%	3516	45.3%
56 Days	7034	0.00%	5670	19.4%	4581	34.9%	3631	48.4%
Average	**6197**	**0.00%**	**5013**	**19.1%**	**3979**	**35.9%**	**3222**	**48.1%**

Abbreviations are as follows: psi (pounds per square inch)

By comparing the data in Table 4.8 and Table 4.9, it can be seen that the base mix designs produce similar compression strengths after equal times of curing. This demonstrates similar strength development and will give a good comparison point. Both studies analyze incorporation of recycled plastic aggregates as coarse aggregates only and at similar replacement rates. It should be noted that Manjunath used 150 x 150 x 150-millimeter (5.91 x 5.91 x 5.91 inch) cubes for compression strength tests while this study used cylinders 8 inches in length and 4 inches in diameter.

A large discrepancy occurs between the decrease in strength between the mixes at all replacement rates. In (Manjunath, 2016), at 10% aggregate replacement with E-plastic aggregates, there is only a small decrease in strength, averaging at only 7.5% decrease among all testing dates. Alternatively, in the mix presented in this research, the mix with the smallest amount of recycled aggregates (15%), there is an average of 19.09% decrease among all testing dates. In the results from (Manjunath, 2016) there is a significant jump in the decrease of strength in the 20% and 30% mixes at 50.8% and 55.0% average decreases, respectively. The jump at the 20% replacement is the largest and most concerning. This is far more than the

Plazrok mixes even at higher replacement rates (35.9% at 30% replacement and 48.1% at 45% replacement).

Table 4.10 Tensile Splitting Strength and Decrease from Control (Manjunath, 2016)

	Control		10%		20%		30%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	623.7	0.00%	623.7	0.0%	456.9	26.7%	348.1	44.2%
14 Days	675.9	0.00%	638.2	5.6%	725.2	-7.3%	449.6	33.5%
28 Days	710.7	0.00%	696.2	2.0%	803.5	-13.1%	551.1	22.4%
Average	**670.1**	**0.00%**	**652.7**	**2.5%**	**661.9**	**2.1%**	**449.6**	**33.4%**

Results have been converted from N/mm^2 (Newton per square millimeter), to psi (pounds per square inch)

Table 4.11 Tensile Splitting Strength and Decrease from Control (Plazrok)

	Control		15%		30%		45%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	359	0.00%	334	6.89%	246	31.40%	191	46.67%
14 Days	347	0.00%	315	9.06%	270	22.10%	235	32.34%
28 Days	331	0.00%	321	3.24%	317	4.21%	259	21.90%
56 Days	335	0.00%	348	-3.81%	283	15.41%	261	22.03%
Average	**343**	**0.00%**	**329**	**3.84%**	**279**	**18.28%**	**236**	**30.73%**

Abbreviations are as follows: psi (pounds per square inch)

Table 4.10 (Manjunath, 2016) and Table 4.11 (Plazrok) compare the tensile splitting strengths of the two mixes. The sizes of the specimens were similar, the size of the specimens in Manjunath's study were 300-millimeter length and 150-millimeter diameter (11.81 inches length and 5.91 inches diameter), whereas the cylinders used for this study were 12 inches in length and six inches in diameter. The control mix from Manjunath has a significantly higher splitting tensile strength compared to the mix in this research, with average strengths at 28 days at 710.7 psi and 331 psi, respectively. The results in both mixes tend to vary, especially in the mix designs with higher rates of replacement. This is reason for concern when designing, more testing should be done to better approximate the relationship between plastic aggregate and splitting tensile strength of concrete. Both mix designs have the highest strength decreases at seven-day testing, up to 44.2% and 46.67%. This could indicate that the bond strength between the replacement aggregates and the cement paste takes more time to gain full strength.

Table 4.12 Flexural Strength and Decrease from Control (Manjunath, 2016)

	Control		10%		20%		30%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	217.6	0.00%	174.0	20.0%	145.0	33.3%	108.8	50.0%
14 Days	435.1	0.00%	420.6	3.3%	290.1	33.3%	181.3	58.3%
28 Days	630.9	0.00%	638.2	-1.1%	623.7	1.1%	362.6	42.5%
Average	**427.9**	**0.00%**	**410.9**	**7.4%**	**352.9**	**22.6%**	**217.6**	**50.3%**

Results have been converted from N/mm^2 (Newton per square millimeter), to psi (pounds per square inch)

Table 4.13 Flexural Strength and Decrease from Control (Plazrok)

	Control		15%		30%		45%	
Days Post Batching	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control	Strength (psi)	% Decrease from Control
7 Days	279	0.00%	275	1.33%	193	30.78%	182	34.71%
28 Days	272	0.00%	250	7.86%	238	12.36%	194	28.50%
Average	**275**	**0.00%**	**263**	**4.59%**	**215**	**21.57%**	**188**	**31.60%**

Abbreviations are as follows: psi (pounds per square inch)

Table 4.12 (Manjunath, 2016) and Table 4.13 (Plazrok) each display the results of flexural strength tests. It should be noted that the sizes of the specimens were different, the size of the specimens in Manjunath's study were 150 x 150 x 700 millimeters (5.91 x 5.91 x 27.56 inches), whereas the prisms used for this study were 3 x 4 x 16 inches. The specimens in Manjunath's study were also cured in clean water instead of a moisture room. When comparing the control mixes for each study, it can be seen the 28-day strength for the mix in this study is significantly less than that of Manjunath (272 psi and 630.9 psi, respectively). However, the flexural strength decrease is not as significant in the results of this study, even at higher replacement rates. As the average decrease at 15%, 30%, and 45% are 4.59%, 21.57%, and 31.60%, respectively. Whereas the results show there is a 7.4%, 22.6%, and 50.3% decrease in the E-plastic mixes at 10%, 20%, and 30% replacement aggregate mixes. This could be due to the bonding strength of the different plastic materials.

Both studies showed decreases in compressive, splitting tensile, and flexural strength as the replacement aggregate was increased in volume. However, the mixes with Plazrok decreased in strength at a lower rate than the mixes with E-plastic. This could be due to the size and shape of the material used as replacement aggregate. Plazrok is very jagged and therefore can bond more fully to a cement paste than most other plastic replacement mixes.

Chapter 5 - Conclusions and Recommendations

This research study utilized various concrete testing methods to test the strength properties of concrete made with increasing amounts of extruded plastic replacement aggregate called Plazrok. The mix designs tested were a control mix and mixes with 15, 30, and 45 percent replacement by volume. The tests strength tests performed were compressive strength, tensile splitting strength, and modulus of rupture. The compressive and tensile splitting tests were performed at seven, 14, 28, and 56 days. The modulus of rupture tests was performed at seven and 28 days. The following conclusions were made from this study:

1. The density of the concrete mixes decreases consistently with the rate of incorporation of Plazrok. This is expected because of the significantly lower specific gravity than the natural coarse aggregate. The lower density concrete can be used to design lighter members. This can assist in lower gravity or seismic load on a structure.
2. The sections where breaks occurred did not show that there was an issue of the Plazrok binding to the cementitious mixture. The area of splitting happened through the aggregate as well as on the edge of the aggregate. This is likely due to the jagged edges of Plazrok, which allow it to better bind to the cement paste.
3. The distribution of the lower density Plazrok was not an issue within the concrete mixes. The spread throughout the molds was consistent and does not need to be addressed in a well-mixed concrete batch.
4. The compressive strength of concrete including Plazrok inversely corresponded to the increase of replacement of natural aggregates. The 28-day compressive strength of the 15, 30, and 45 percent replacement rates had 18.1, 35.6 and 45.3 percent decreases in strength in comparison to the 28-day strength of the control mix. From the findings in

this study the resulting compressive strength of concrete can be found using the equations shown in Figure 4-3.

5. The base design mix is specified for 4000 psi. The compressive strength with 15% and 30% replacement aggregates was 5260 and 4140 psi, respectively. This means it still meets specifications and can be used as designed. More experimentation should be done and cylinders should be made and tested for the specific mix design used before using as structural concrete.
6. The tensile splitting strength decreased as the replacement rate of Plazrok increased. The development of strength curve varied from mix to mix. This could be due to the process of testing and the volatile method of failure for unreinforced concrete members in tension. Additional testing should be performed to confirm tensile splitting behavior. Equation 4-7 can be used to predict the tensile splitting strength when given the compressive strength for this mix design.
7. The modulus of rupture tests showed a similar trend to that of the splitting tensile test in that there is a decrease in strength as there is an increase in replacement rate. The trend of strength increase over time is varied and is not consistent between the different concrete mixes. There was little change in the strength of each mix between seven- and 28-day testing. This shows that almost full strength can be expected at an early curing age. Additional testing should be performed to confirm tensile behavior. Equation 4-13 can be used to predict the modulus of rupture when given the compressive strength of the concrete mixture.
8. The largest issue with using this product will likely be local availability. If Plazrok is to become a widely used replacement aggregate, manufacturing facilities must be near to a

concrete batching plant if it is to be used in large capacities reasonably. Plazrok does have the benefit of low specific gravity which will lead to lower shipping costs than that of natural aggregate. However, natural aggregates can be found and produced almost anywhere on earth and will likely not have to be shipped as far. The shipping cost for aggregates can significantly increase the cost of the concrete.

9. The structural engineering field must develop a demand for Plazrok and other recycled aggregates for recycling centers to be incentivized to develop recycling methods to produce it.

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Appendix A - Concrete Mix Design

MCM Midwest Concrete Materials

Concrete Mix Design Submittal

DATE: 08/26/2020 — **No. 20034742 Version 1**

Mix Code: **85531100** Description: **4000# 65/35**

			Design	Tolerance
Customer				
Contact	Lauren Costello	Air Content	3	
Office Phone		Slump	4.0	
Project Name	KSU Engineering - Plastic Aggregate	Design Strength	4000	psi
Project Contact	Laruren Costello	Unit Weight	146.7	lb/ft3
Usage/Placement	Standard Commercial Interior	W/C Ratio	0.45	

This submittal and mix design is confidential and protected information submitted for engineering review. Any unauthorized distribution of this mix design to any outside party without written consent of Midwest Concrete Materials will be grounds for prosecution

Material Type	Description	Source Supplier	Design Quantity	Specific Gravity	Volume (ft3)
Cement	ASHGROVE TYPE I/II CEMENT	Ash Grove Cement Co.	564 lb	3.15	2.87
Fine Aggregate	MCM KP FINE AGGREGATE	Midwest Concrete Materials	2024 lb	2.63	12.34
Coarse Aggregate	BAYER ZEANDALE ASTM 57/67 - CA5	Bayer Construction Co.	560 lb	2.60	3.45
Water	WATER	Midwest Concrete Materials	30.4 gal	1.00	4.06
Admixture	GRACE MID-RANGE WATER REDUCER	W.R. Grace	25 lq oz	-	-
Coarse Aggregate	MCM KP CA-4	Midwest Concrete Materials	560 lb	2.58	3.48
		Air Content	**3.00 %**	**–**	**0.81**
		Yield	**3962 lb**	**–**	**27.01**

NOTES

Prepared By:

Chaz Hill

Chaz Hill Quality Control

Appendix B – Permissions

MCM Permissions

FW: Mix Designs

Katie Loughmiller <loughmil@ksu.edu>
Sun 3/28/2021 8:49 PM
To: Lauren Costello <laurencostello@ksu.edu>

Here is the email from Chaz.

From: Charles Hill <Chaz.Hill@midwestconcretematerials.com>
Sent: Friday, March 26, 2021 9:53 AM
To: Katie Loughmiller <loughmil@ksu.edu>
Subject: Re: Mix Designs

This email originated from outside of K-State.

Katie,

That would be fine. Please share the paper, I would love to check it out!

Thank you,

Chaz Hill
Midwest Concrete Materials, Inc.
785.564.0814

> On Mar 26, 2021, at 9:22 AM, Katie Loughmiller <loughmil@ksu.edu> wrote:
>
> Chaz: Lauren is wrapping up her thesis work on plastic aggregates and we wanted to just loop back around and confirm that it would be okay for her to include the original mix designs you shared with us in her thesis. Once she has it finalized I would be happy to send you a copy so you can see what she found with her testing.
>
> Katie
>
> Katie Loughmiller
> Assistant Professor
> Martin K. Eby Distinguished Professor
>
> <image002.jpg>
> G.E. Johnson Department of Architectural Engineering and Construction Science
> 2037 Seaton Hall
> 940 N. 17th St.
> Kansas State University
> Manhattan, KS 66503
> (785)-477-2732

From: Charles Hill <Chaz.Hill@midwestconcretematerials.com>
Sent: Tuesday, September 1, 2020 2:00 PM
To: Lauren Costello <laurencostello@ksu.edu>
Cc: Katie Loughmiller <loughmil@ksu.edu>
Subject: RE: Mix Designs

Lauren,

Both mixes are designed for a 4" slump plus/minus one inch. So you should be good to batch at 5". Beyond that, I would recommend using additional water reducer to achieve higher slumps. How much and of which materials do you need?

Thanks,

Chaz Hill
MCM Midwest Concrete Materials
Office: 785.776.8811
Cell: 785.564.0814
Fax: 785.776.1816
chill@4mcm.com
www.midwestconcretematerials.com

From: Lauren Costello <laurencostello@ksu.edu>
Sent: Tuesday, September 1, 2020 9:27 AM
To: Charles Hill <Chaz.Hill@midwestconcretematerials.com>
Cc: Katie Loughmiller <loughmil@ksu.edu>
Subject: Re: Mix Designs

Chaz -

A few things, I think that the best way to make my mixes would be for me to mix the batches myself here on campus. We have a mixing drum that can hold 6 cubic feet (which is about what I will need for each mix design) but only if it has a slump of 5 inches. Is there a basic indoor, normal-weight concrete mix that you have with a 5 inch slump that I could use instead of the one you provided which has a 4 inch slump?

Also, would there be a good way for MCM to deliver the material to campus so that we can mix it here?

Thank you,

Lauren Costello

Kansas State University

Architectural Engineering

From: Charles Hill <Chaz.Hill@midwestconcretematerials.com>
Sent: Wednesday, August 26, 2020 11:28 AM
To: Lauren Costello <laurencostello@ksu.edu>

Cc: Katie Loughmiller <loughmil@ksu.edu>
Subject: Mix Designs

Lauren,

Attached is our standard lightweight concrete mix design as well as our standard commercial interior mix design. Let me know how I can help with your research project.

Thank you!

Chaz Hill
MCM Midwest Concrete Materials
Office: 785.776.8811
Cell: 785.564.0814
Fax: 785.776.1816
chill@4mcm.com
www.midwestconcretematerials.com

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