

Mechanical properties of concrete with recycled plastic coarse aggregate partial replacement

by

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Abstract

¶ Concrete is the second most used material in the building industry, after water (Global Cement and Concrete Association, 2020). Concrete is made up of cement, water, and natural aggregates such as fine and coarse aggregates. To prevent the earth from losing natural resources to make concrete, a replacement for these materials must be found. Many researchers have found that a possible replacement for coarse aggregate in concrete is recycled plastic waste. These studies have been conducted to test the mechanical properties: compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity of concrete with partial plastic waste replacement as coarse aggregate. The studies differ from each other based on the type of plastic used, the water-to-cementitious ratios (w/c), the amount of plastic replacement, and the concrete mix. This thesis examines and compares the results of previous studies/tests conducted on concrete with the replacement of coarse aggregate with plastic to possibly find trends or recommendations for future use. Several tables and graphs that summarize the findings in these studies were made. For the compressive strength and the splitting tensile strength, results from 10%, 15%, and 20% replacements were tabulated and graphed. However, due to the lesser number of tests done on the modulus of rupture, only 10% and 20% replacement results were tabulated and graphed. The graphs were made based on the resulting strength after the partial replacement vs curing days. In contrast, the graph conducted on the modulus of elasticity was based on the resulting modulus of elasticity vs the percentage of plastic replacement. It was shown that up to a certain level, the properties of plastic waste could be suitable to produce new concrete. However, due to the varying results from the studies it was difficult to find trends as each study had a different concrete mix with not much information or discussion provided. Shown in most studies examined, as the amount of plastic waste replacement increases the lower

the compressive strength, splitting tensile strength, and modulus of elasticity. However, the modulus of rupture resulted in a slight increase or no change in strength after the plastic replacement. Very little information was provided in the studies examined herein, which led to no common trends or conclusions being found. This thesis may be used as a good resource to find summarized tables and graphs on the previous studies examining the mechanical strength of concrete containing partial plastic waste replacement for coarse aggregate.

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Dedication

I dedicate this thesis to my beloved parents and siblings.

Chapter 1 - Introduction

Concrete is the most used construction material in the building industry, after water (Global Cement and Concrete Association, 2020). Concrete is composed of cement, fine aggregates (sand – aggregates passing the 3/8-inch sieve) and coarse aggregates mixed with water which chemically reacts causing the concrete to harden with time, hydration process. This building material is used for the construction of foundations, beams, columns, slabs, and other load bearing or non-load bearing elements. Two main types of concrete are normal weight concrete (NWC) and light weight concrete (LWC). LWC is defined by the American Concrete Institute (ACI) as having a weight less than 135 pounds per cubic foot. The prime difference between normal weight (standard) concrete mixes and lightweight concrete mixes is the aggregate used in the concrete mixture (Spangler, 2022). Crushed stone, which is dense in its size and adds to the weight of the concrete mix, is typically used in standard, NWC, concrete mixes. However, lightweight concrete uses a variety of alternate aggregate materials such as porous rock, manufacturing byproducts (fly ash or slag), clay, and shale. These materials get treated with a heat process that expands the material and creates a series of internal pores in the aggregate causing the concrete to have a lower mass per volume (Spangler, 2022). This causes the lightweight concrete to have an increased capacity for moisture absorption and can take up to three times longer than standard aggregate concrete to dry. This is a major disadvantage, which is why NWC is still more commonly used. Due to this, only studies on NWC are discussed in this thesis.

Natural aggregates take up 60%-80% of the total volume of the concrete mix and are collected from gravel, crushed stone, rocks, and sometimes recycled concrete. After they are acquired by blasting in stone quarries, these pieces are broken into smaller pieces by hand or

crusher machines (Mahajan, 2023). Coarse aggregate is considered the essential aggregate because it occupies the largest volume in the concrete mix. Typically, the dividing line between coarse and fine aggregate is the 9.5 mm (0.375 in) sieve (Seegebrecht, 2020). However, some consider 4.75 mm (0.19 in) sized aggregate as coarse. Coarse aggregate has a major effect on concrete properties such as abrasion resistance, hardness, elastic modulus, and other characteristics like increased durability, strength, and a low cost (Mahajan, 2023). Since the demand for concrete has increased due to the industrialization, urbanization, and population increase, more natural rocks for coarse aggregates are needed leading to a faster reduction in natural resources and may welcome natural disasters in the form of global warming and land sliding (Ahmad et al., 2021).

A way to decrease the usage of natural rocks in concrete is using plastic waste as a partial replacement for coarse aggregate. With the increase of plastic use globally this seems like a reasonable result for both issues, the need for more natural rocks and the increase in plastic waste which will be diverted from landfills. Studies have been conducted on the use of plastic waste as a partial replacement for coarse aggregate in the concrete mix and how it affects the engineering properties (mechanical properties) of the concrete. The results of several studies are discussed in this thesis to compare their findings and find possible common trends.

Chapter 2 presents plastic waste and why it is a problem along with the types of plastic, plastic recycling, and the preparation of plastic aggregates to be utilized in concrete. Next, Chapter 3 presents the mechanical properties of concrete, compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity, and why they are important. Additionally, this chapter includes the testing methods for each property and how they differ. Lastly, this chapter presents the mechanical properties of concrete after the partial plastic waste

replacement for coarse aggregate. Lastly, Chapter 4 presents the conclusion of this thesis and recommendations for the future.

Chapter 2 - Plastic Waste

The use of plastics has astronomically increased since 1920 since plastic was first developed (Babafemi et al., 2018). Primarily due to its many advantages, compared to materials like glass or metal: lower cost, high strength-to-weight ratio, low density, durability, and easily worked and shaped. However, the increased use of plastic is very detrimental to the environment because of its non-biodegradable behavior. Plastics are chemically unreactive in the natural environment causing them to persist for decades and even centuries (Lei, 2016). Figure 2.1 indicates the amount of plastic waste emitted to the ocean per capita in 2019 showing that plastic waste harms both the living habitats on land and in the ocean (Ritchie, 2018). The global plastic production in 2019 is reported to have increased to 417 million metric tons (459 million tons) worldwide with most of it being used for one-off disposable consumer products contributing to the increase of plastic waste (Lei, 2016). Europe alone in 2012 consumed 45.9 million tons of plastics with 25.2 million tons ending up in the waste stream. Examining Europe further, “Approximately 26% of the total plastic waste was mechanically recycled, 0.3% was collected for feedstock recycling, 35.6% was recovered for energy, and the remaining 38.1% was disposed” (Lei, 2016).

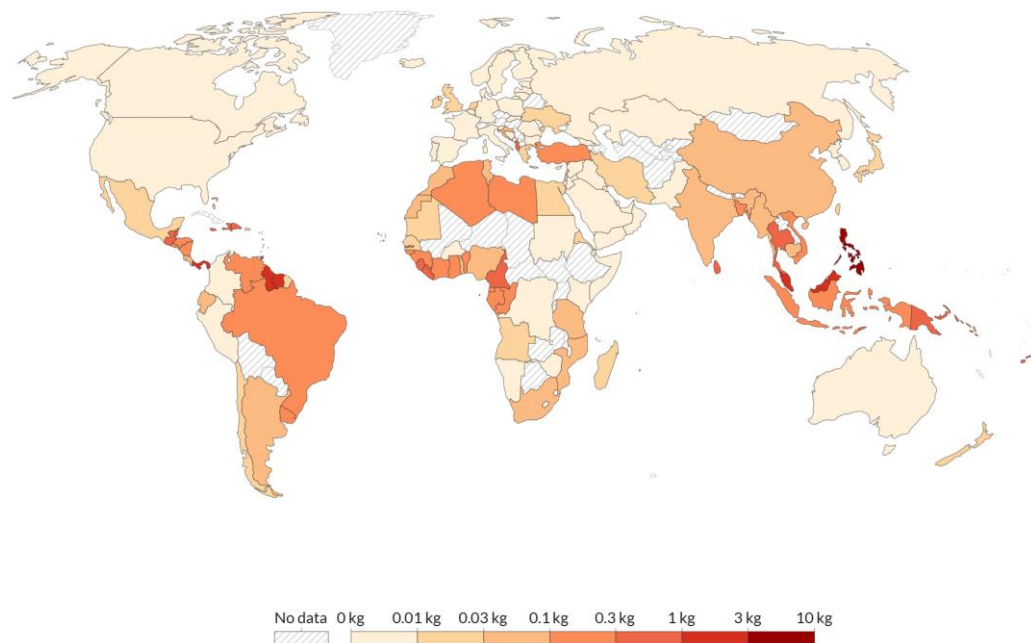


Figure 2.1 Plastic waste emitted to the ocean per capita, 2019. (Ritchie, 2018).

2.1 Types of Plastics

Thermosets and thermoplastics are the two major categories of plastic. The primary difference between the two is thermoset is a material that strengthens when heated but cannot be remolded or heated after the initial forming (Thermoset vs. Thermoplastics, nd). This means that thermoset components become set in their physical and chemical properties after an initial heat treatment and will no longer be affected by additional heat exposure. On the other hand, thermoplastics can be reheated, remolded, and cooled as necessary without causing any chemical changes (Thermoset vs. Thermoplastics, nd). Thermoplastic polymers are known for their versatility and recyclability since the pellets soften when heated and become more fluid as more heat is administered. This allows thermoplastics to be remolded and recycled without negatively affecting the material's physical properties. As a result of these physical and chemical

properties, thermoplastic materials have low melting points while thermoset products can withstand higher temperatures without loss of their structural integrity (Thermoset vs. Thermoplastics, nd). Thermoplastic polymers are more commonly used, and they include polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polypropylenes (PP). Another common type of plastic waste that has increased in recent years is E-plastic waste that comes from electronic devices.

PET is a clear tough plastic widely used for making liquid containers (bottles). It has excellent tensile and impact strength, chemical resistance, clarity, processability, color ability and reasonable thermal stability (Awaja, 2005). A major benefit of PET products is their slow decomposition rate making them a non-degradable plastic. However, being a non-degradable plastic waste means the disposal of it has huge negative environmental impacts – filling landfills. The world's annual consumption of PET plastic bottles is approximately ten tons which grows approximately 15% each year, while the number of recycled bottles is extremely low. Due to PET being the most common plastic type used and due to its' environmental impacts when it is discarded, recycling it to improve waste management is recommended (Awaja, 2005).

HDPE is commonly used in many applications such as plastic bottles, toys, chemical containers, and pipe systems. HDPE is decomposable and suitable for blow-molding items such as food and beverage containers because it does not leak. HDPE is safe, long lasting, and is the most environmentally stable type of plastic since it does not emit dangerous fumes into the environment. Additionally, HDPE is UV resistant, non-leaching, cost-effective, highly versatile, and affordable (Solutions, 2022).

PP is made from a combination of propylene monomers and is commonly used in packaging for consumer products, plastic parts for various industries including the automotive

industry, special devices like living hinges, and textiles. PP has a relatively slippery surface which can make it a possible substitute in many applications. However, a negative aspect of this quality is the difficulty bonding PP to other surfaces which is discussed further in the following paragraphs. Some advantages of PP include chemical resistance, elasticity, insulation, and transmissivity (Creative mechanisms staff, 2019).

PET plastics have a number “1” on them which means they are the easiest to recycle. PET plastics are recycled into new bottles, polyester for fabrics and carpet, fill for bumper cars, or fiberfill for sleeping bags and jackets. This is why they are used the most in concrete compared to other thermoplastics. HDPE plastics have a number “2” on them which means they are the second easiest plastic to recycle. Clear HDPE containers are easily recycled back into new containers while colored HDPE are converted into plastic lumber, lawn and garden edging, pipes, rope, or toys. PP plastics have a number “5” on them which means they are the fifth easiest plastic to recycle PP. PP plastics are hard to recycle due to the differences in the varieties of type and grade making it difficult to achieve consistent quality during recycling which is why they are not commonly used (Sea Studios Foundation).

Another common plastic waste widely used comes from electronic waste (E-Waste). Worldwide, people generated an estimated 44.7 million metric tons (49.3 million tons) of electronic waste in 2016, with the United States of America (USA) responsible for 6.3 million tons, or 14% of the world’s total (Methods to Remove Plastics in E-waste, 2022). E-waste contains valuable reusable materials: precious metals, gold, platinum, copper wiring – and plastics, which when harvested from the discarded devices can be used to make new products (E-Plastic). Few safe or efficient ways to recycle these plastics exist due to their different polymer composition than most recyclable items - soda bottles or milk jugs that are made from single

polymers. For example, plastics in cellphone cases are made from a more complex polymer blend (Methods to Remove Plastics in E-waste, 2022).

2.2 Plastic Recycling

While the production of plastics cannot be halted, recycling the plastic waste may be a solution to reduce their negative environmental impact (Babafemi et al., 2018). Chemical recycling and mechanical recycling are the two major processes of recycling plastics. Chemical recycling is achieved by depolymerization into monomers or partial depolymerization into oligomers (Awaja and Pavel, 2005). However, a main disadvantage of chemical recycling is its high cost. Therefore, the focus of this thesis is the use of mechanically recycled plastics since it is more common, simpler, environmentally friendly, and requires low investment.

The mechanical recycling of plastics normally consists of contamination removal by sorting, washing, drying, and melt processing (Awaja, 2005). The sorting process consists of separating the desired plastic waste from other plastic materials. This step is especially important and critical because deterioration of the plastics can occur during processing if high levels of contamination by other materials occurs (Awaja, 2005). Sorting can be either done manually or by other separation techniques based on the difference between the chemical or physical properties of the plastic compared to the other materials. After the sorting process, the plastic is grounded into flakes to make it easier to process and is then washed. The flakes are washed two ways: aqueous washing and solvent washing (Awaja, 2005). Next is the essential step of drying which minimizes the moisture content in the flakes. This reduces the hydrolytic degradation effect and leads to higher melt strength. Most manufacturers use drying conditions ranging from 140-170°C (284-338°F) and 3 to 7 hours. Lastly, the flakes are melted and

processed into useful granules. However, this results in the plastic having a low molecular weight due to the degradation reactions from the contaminants that are still present after the sorting process (Awaja, 2005). This is the main disadvantage of mechanical recycling and is still being looked at by researchers and manufacturers. Figure 2.2 shows a simplified flow chart of a plastic waste management operation (Rebeiz, 1995).

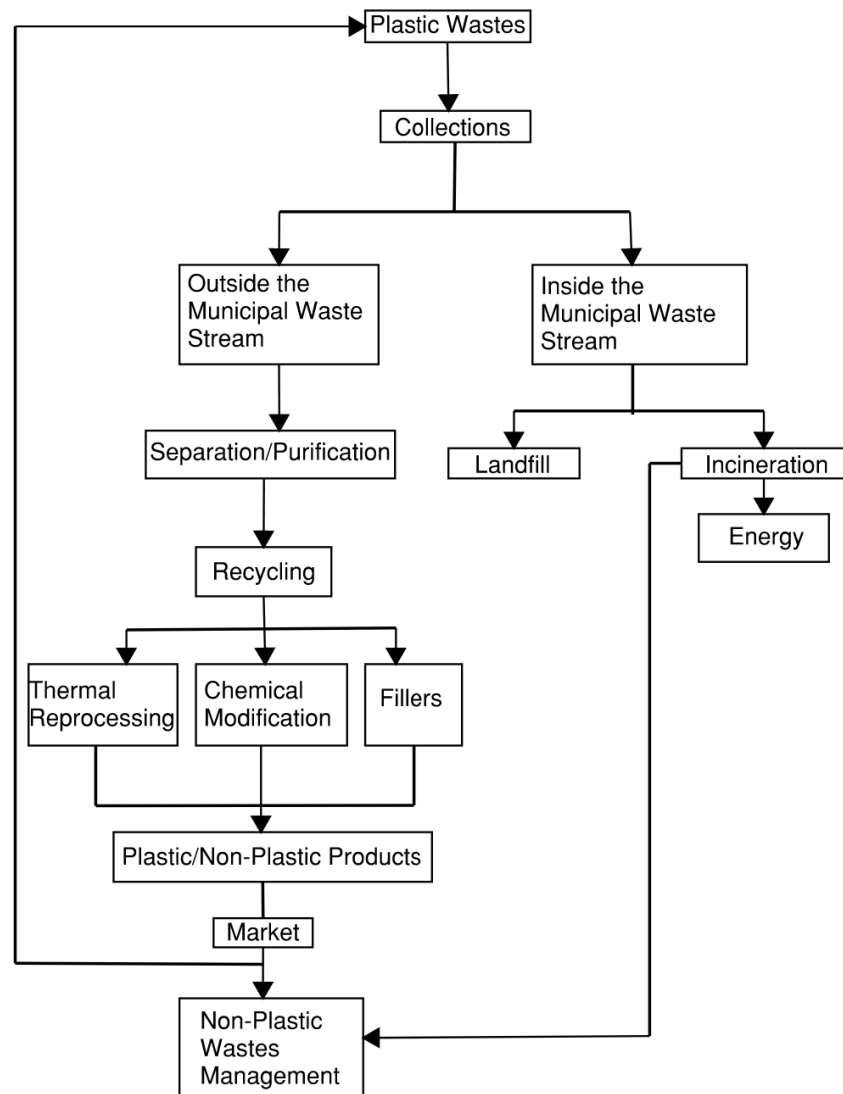


Figure 2.2 Plastic waste management process recreated from Rebeiz, 1995

E-Plastic waste recycling is slightly different from thermoplastic recycling since E-Plastics have a different polymer composition. Scientists at the Illinois Sustainable Technology Center discovered a way to separate mixed polymers, so they can be recycled and used to make new products. Their goal was to find environmentally safe and healthy ways to recycle the abundant amount of mixed-plastic waste in electronics so they could be reused (Methods to Remove Plastics in E-waste, 2022). They focused on the mixed plastics in electronics waste, and how that could be a valuable source of reusable polymers. After some research, they discovered an energy-efficient chemical solvent that could recover polymers from complex plastic blends, in a nontoxic and nondestructive way. The process involves using the solvent to dissolve industrial polymers so the plastic polymers can be recovered (Methods to Remove Plastics in E-waste, 2022).

2.3 Preparation/utilization of Plastic Aggregates

Many ways to prepare plastic waste to be used as aggregate in concrete exist. Several research studies have been done regarding the use of plastic waste as aggregate replacement in concrete with each study having a unique way of preparing the plastic waste. One of the ways to prepare plastic aggregates will be discussed below.

In a study done by Saikia and de Brito, three types of plastic aggregate were used: (1) a shredded fine shaped PET aggregate with sieve size from 5.6-2 mm (0.22-0.08 inch), (2) a shredded coarse shaped PET aggregate with sieve size from 16-4 mm (0.6-0.16 inch), and (3) a heat treated pellet-shaped product directly collected from waste PET treatment plant with sieve size 5.6-2 mm (0.22-0.08 inch) as aggregate in concrete (Saikia and de Brito, 2012). The two shredded types of aggregates were obtained after mechanical grinding of PET waste. The pellet-

shaped PET-waste fraction was produced from coarse plastic flakes in a reactor according to predetermined conditions (Saikia and de Brito, 2012). To extract the volatile contaminants, the waste plastic, material, was heated and melted such that the volatile contaminants were properly removed. The extrusion process limits the occurrence of secondary reactions during the melting stage. After passing through a spinneret, the melt is collected in a cooling bath that solidifies the polymer before being granulated in a rotary cutter in water. The mixture of water and grains of polymer is subjected to a vibratory separator and then the grains of polymer (plastic pellets) are centrifuged to remove excess water (Saikia and de Brito, 2012).

Chapter 3 - Mechanical Properties of Hardened Concrete

Many studies to observe the mechanical properties and behavior of concrete with recycled plastic as a partial replacement for coarse aggregate have been conducted. A variety of mechanical properties, such as compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and stress-strain curves define the structural behavior of concrete. These properties must be carefully analyzed to ensure the concrete with partial replacement of recycled plastic aggregates reach the required strengths and have similar behavior to traditional concrete.

For this thesis, a total of twelve research studies were examined, Ghaly and Gill (2004), Saikia and De Brito (2012), Prasanna and Rao (2014), Akram, Sasidhar, and Pasha (2015), Manjunath (2016), Saxena, Gupta, Sharma, Chaudhary, and Jain (2016), Shamnugapriya and Santhi (2017), Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017), Needhidsan, Ramesh, and Prabu (2020), Costello (2021), and Islam and Shahjalal (2021) along with a discussion and comparison of their results. Table 3.1 provides a summary of the literature reviewed. The w/c ratio used is indicated along with the standard used for testing and the size of the replacement aggregate. Figure 3.1 shows the plastic aggregate used these authors

Current research indicates varying results due to many factors such as: different testing methods, types of recycled plastic, and size or shape of the replacements aggregate. However, most research reviewed indicated a decrease in the mechanical properties of concrete with recycled plastic aggregate replacement compared to those only containing natural aggregates. This may be due to the decreased in adhesive strength between the surface of the recycled plastic and the cement paste (Akram, 2015). Plastic is also considered to be a hydrophobic material, water-resistant which may restrict the water necessary for cement hydration from entering through the structure of the concrete specimens during the curing period (Zainab et al., 2008).

Table 3.1 Summary of Literature Review

Reference document	Plastic	w/c ratio	Standard	Comp. Test	Tensile Test	Flexural Test	MoE Test	Agg. Size mm (in)
Ghaly and Gill (2004)		0.42, 0.54, 0.69		X			X	9.5 (3.8)
Saikia and De Brito (2012)	PET	0.61, 0.65, 0.74	EN	X				8 (0.3)
Prasanna and Rao (2014)	E-Plastic		IS	X	X			10-20 (0.4-0.8)
Akram et. al. (2015)	E-Plastic	0.5	IS	X	X			20 (0.8)
Manjunath (2016)	E-Plastic	0.5	IS	X	X	X		12.5-20 (0.5-0.8)
Saxena et al. (2016)	PET	0.45	ASTM				X	4.75-20 (0.19-0.8)
Shamnugapriya & Santhi (2017)	HDPE	0.42	IS	X	X	X		12.5 (0.5)
Tamang et. al. (2017)	PET	0.45	IS	X	X	X		20 (0.8)
Needhidsan et. al. (2020)	E-Plastic	0.5	IS	X				
Costello (2021)	Plazrok	0.45	ASTM	X	X			20 (0.8)
Islam and Shahjalal (2021)	PP	0.45, 0.55	ASTM				X	
EN: European National Standard. ASTM: American Society for Testing and Materials. IS: Indian Standard. Comp.: Compressive strength. MoE: Modulus of Elasticity								



Ghaly and Gill (2004)



Saxena et al. (2016)



Shamnugapriya & Santhi (2017)



Tamang et. al. (2017)



Needhidsan et. al. (2020)



Costello (2021)

Figure 3.1 Plastic Aggregates used.

3.1 Compressive Strength

3.1.1 Importance of Compressive Strength in Concrete

For engineering purposes, concrete is specified by its compressive strength. A minimum compressive strength of concrete at 28-days defines the structural design parameters for the concrete elements – lower concrete compressive strength will require larger structural element sections (increased member sizes); otherwise, the concrete will fail and cause a structure to collapse if the design minimum compressive strength is not reached, excluding any safety factors. Concrete gains strength as the cementitious material hydrates which occurs over time; therefore, it takes an unknown amount of time to gain 100% strength, complete the chemical process. The rate of concrete compressive strength gain is higher during the first 28 days of casting which is why test methods use the 28-day mark for compressive strength (Compressive Strength of Concrete, 2022). Concrete compressive strength for normal construction varies from 20 MPa (2900 psi) to 40 Mpa (5800 psi) and higher in commercial and industrial structures (Mahajan, 2022).

Several factors impact the compressive strength gain in concrete: aggregate size, air entrainment, and water-cementitious material ratio. First is the size of the aggregate. When a smaller aggregate is used that would mean a smaller surface area is available for the bond between the aggregate and cement which can cause a decrease in strength (Compressive Strength of Concrete, 2022). The second factor contributing to the compressive strength is the amount of air entrainment. Concrete air entrainment was developed to prevent damage from freeze-thaw action along with an improved workability of concrete (Compressive Strength of Concrete, 2022). The third factor is the water-to-cementitious ratio (w/c). Cement is the powder component of concrete that becomes a binder when mixed with water which allows concrete to

set, strengthen, and harden (Cementitious Materials, n.d). Secondary cementitious materials such as fly ash, limestone, silica fume, and natural calcined pozzolana may be used as replacement for cement and are called cementitious additions. The most common type of cement used is Portland cement, which is made by heating sources of iron, lime, silica, and alumina to high temperatures in a kiln then grinded into a fine powder (Cement Types, n.d). The cement materials in a concrete mixture act as binding material for concrete and it requires water for the hydration process to occur. While excess water is beneficial to the workability and finishing of concrete, excess water can leave large spaces between the cement paste and aggregate once the concrete hardens and the excess water evaporates (Compressive Strength of Concrete, 2022). Concrete is a porous material. If water enters the voids in the concrete and freezes, cracks in the concrete can occur leading to durability and strength issues. The w/c ratio should be analyzed carefully when specifying and mixing the concrete. Other factors impacting the compressive strength in concrete include cement strength, quality of concrete material, and quality control during production. However, these do not highly affect the compressive strength of concrete as much as the factors listed above.

3.1.2 Test Methods to Determine Compressive Strength

Three common tests methods exist to determine the compressive strength of concrete: the American Society for Testing and Materials ATSM C39 cylinder test, the Indian Standard IS 516-1959 cube test, and the European National Standard EN 12390-3 cylinder test. This section presents these 3 methods. The most common testing method for concrete compressive strength in the USA utilizes the American Society of the International Association for Testing and Materials (ASTM) standards. *ASTM C39 Standard Test Methods for Compressive Strength of*

Cylindrical Concrete Specimens determines compressive strength of cylindrical concrete specimens and correlates this strength to full in-place specimens (elements within a structure to be tested). This test method begins with the cylinders being taken from the moisture room and kept covered with wet burlap to keep them moist. The ends of the cylindrical concrete specimens are prepared to ensure it has a smooth and parallel bearing surface that is perpendicular to the applied load by using bonded sulfur mortar caps. It is required that the ends of the test specimens be plane within 0.05 mm (0.002 inch) and the deviation of end faces from being perpendicular to the specimen axis is less than 0.5 degrees (1 mm in 100 mm or 0.12 inch in 12 inches). Next, the bearing surfaces of the machine are cleaned then the specimen is placed on the lower bearing block and aligned with the upper bearing block, using the rings on the bottom block to center it. Before testing and applying load, the load indicator is verified at zero. The load is then fully applied until it reaches about 10% of the estimated load. Then the load is applied to the cylinder continuously at a rate of movement corresponding to a stress rate of 0.25 MPa/s (35 psi/s). The load should be applied until the cylinder reaches its peak load and decreases steadily, and the specimen displays a well-defined fracture pattern as shown in Figure 3.1 Types 1 to 4. When testing with unbonded caps, corner fractures similar to Types 5 and 6 shown in Figure 3.2 may occur before the ultimate capacity of the specimen has been reached. In that case, the load should continue to be applied until it is certain the ultimate capacity has been reached. The cylinder is then pulled out of the machine and the type of fractures are determined and recorded along with the load. Lastly, the compressive strength is calculated using Eq. 3.1 and Eq. 3.2 (*ASTM Standard C39*).

SI units:

$$f_{cm} = \frac{4000P_{max}}{\pi D^2} \quad \text{Eq. 3.1}$$

Inch-pounds units:

$$f_{cm} = \frac{4P_{max}}{\pi D^2} \quad \text{Eq. 3.2}$$

where:

f_{cm} = compressive strength, MPa (psi);

P_{max} = maximum load, kN (lbf);

D = average measured diameter, mm (in).

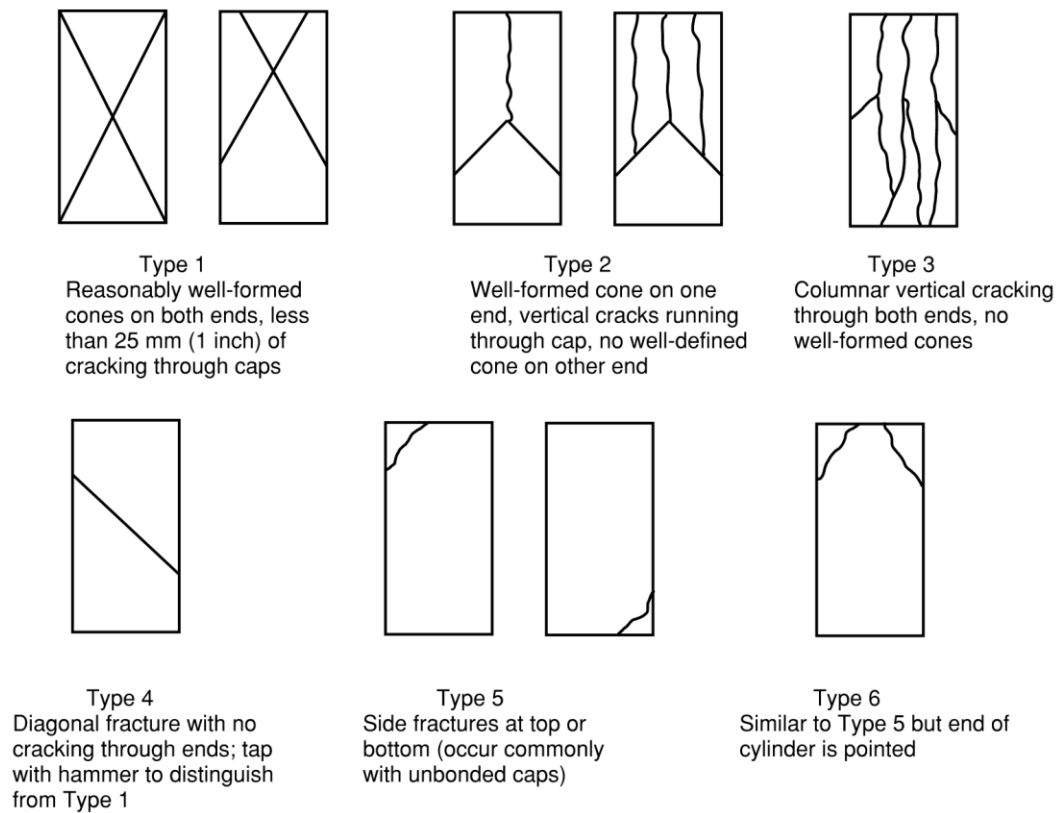


Figure 3.2 Concrete Fracture Type of Compressive Strength of Cylindrical Specimens recreated from ASTM C39

The second method of determining concrete compressive strength test is the IS 156-1959 cube test. This standard method is common outside the USA to determine the compressive strength of concrete is the cube test. In the literature reviewed for this thesis, such as Tamang (2017), a test method used for determining the compressive strength of concrete with partial plastic aggregate replacement was the Indian Standard *IS 516-1959 Methods of Tests for Strength of Concrete*. Depending on the size of the aggregate either 10 cm or 15 cm (4 inch or 6 inch) cubes are used, but 15 cm (4 inch) cubes are more common (Mishra, 2020). For this compressive strength test method, the cubes are first prepared and cured in water for 24 hours before being tested. The specimen is removed from the water after the specified curing time and excess water is wiped off. The specimen is then placed in the compression testing machine in a manner that the load can be applied to opposite sides of the cube. The load is then applied gradually and continuously until the specimen fails. This is similar to the ASTM C109 test procedure in a manner where cubes are loaded on opposite sides for compression. Finally, the maximum load is recorded, and any unusual features or cracks are noted. The compressive strength is determined by dividing the maximum applied load by the cross sectional area of the specimen (Indian Standard, *IS 516-1959*).

The third method of determining concrete compressive strength test is the EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens. This method is the European Standard which is commonly used in European countries. Similar to the ASTM C39 procedure, the cylinders are subjected to a compression test on a testing machine with a constantly increasing load until any of the fracture types shown in Figure 3.3 appear. The maximum load is then recorded, and the compressive strength is calculated using Eq. 3.3 (EN 12390-3).

$$f_c = \frac{F}{A_c} \quad \text{Eq. 3.3}$$

where:

f_c = compressive strength, MPa;

F = maximum load at failure, N;

A_c = the cross-sectional area of the specimen on which the compressive strength acts, mm².

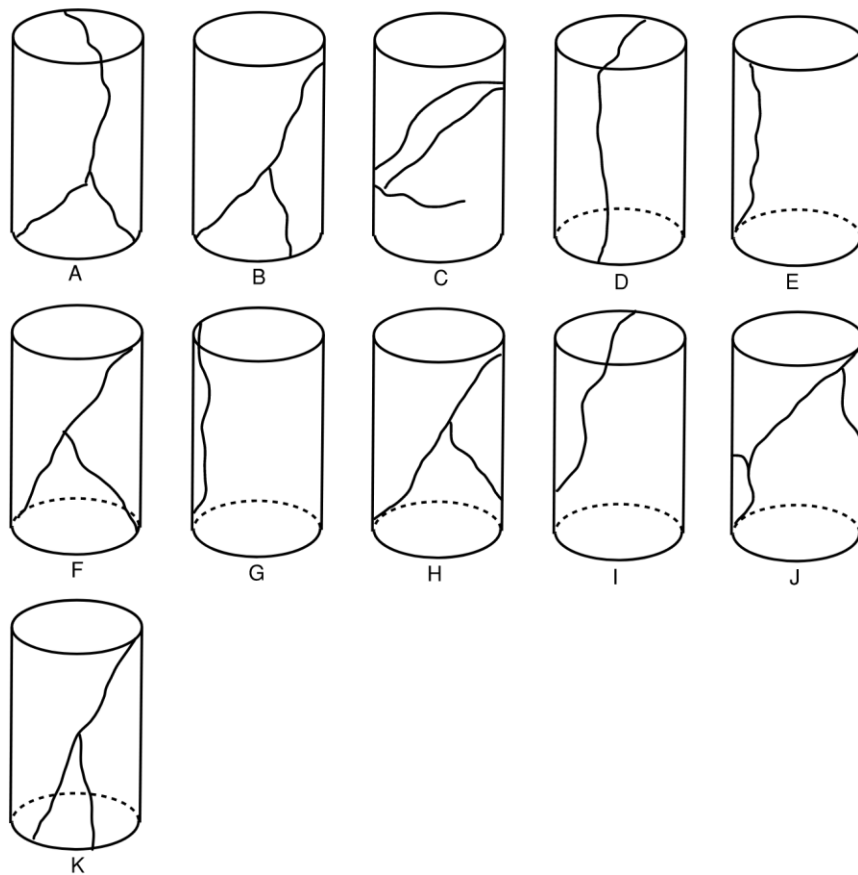


**Figure 3.3 Concrete Fracture Type of Compressive Strength of Cylindrical Specimens
recreated from EN 12390-3**

In 1995, the Transportation Research and Development Bureau of New York State Department of Transportation published Special Report 119 which consisted of comparing concrete cylinder and cube specimens for compression testing through a survey of past research, including testing procedures, factors affecting the cylinder/cube strength ratio, and conversion factors and equations. Elwell and Fu found that the main difference between cylinder and cube testing procedures is capping. As explained earlier, the ends of the cylindrical specimens must be capped with a suitable material so that they are parallel to the testing machine. However, cubes are not capped because they have plane and parallel edges to the testing machine. Elwell and Fu stated that some factors affecting the cylinder/cube strength ratio are: 1) casting, curing, and testing procedure; 2) specimen geometry; 3) level of strength; 4) direction of loading and machine characteristics; and 5) aggregate grading. Past research indicated that it is very difficult to predict the relationship between cylinder and cube strengths and showed the most common cylinder/cube strength ratios are between 0.65 and 0.90. Elwell and Fu concluded that replacing cylinder testing with cube testing is not recommended.

In a more recent article, published in 2022 by TeamCivil titled Compressive strength of concrete cube vs. cylinder, it was stated that the compressive strength of a cube specimen is larger than the compressive strength of a cylindrical specimen using the same mix. The main cause for this difference in strength is the different length to diameter ratios for cubes and cylinders. In addition, the testing machine's top platen has a greater surface area to interface with cubes than the cylinders which will require higher stress to fail. Both test procedures use steel plates that are positioned above and below the specimen that have no lateral expansion in contrast to the concrete specimen itself. As a result, the steel prevents the concrete from expanding laterally. This causes frictional tension developing between the plate and the

specimen and a shear stress occurring inside the specimen due to the two stresses acting on the specimen: 1) friction stresses between the steel plates and the concrete specimens and 2) compressive force on the specimen. Since the cube specimens are shorter in height, they are affected by the restraint caused by friction between the specimens and the steel plate while cylinders have unaffected parts. As a result, the cube specimen experiences a greater stress than the cylinder specimen.

In a question and answer (Q/A) page from the American Concrete Institute (ACI) website titled “*Using cube tests in lieu of cylinder tests*” it was stated that the lower height to width ratio of cube specimens results in a higher apparent strength than what would be obtained using cylindrical specimens.

3.1.3 Compressive Strength of Concrete After Plastic Replacement

The compressive strength of concrete with natural aggregates varies from 20 MPa to 40 MPa (2900 psi to 5800 psi) and higher in commercial and industrial structures. Ten research documents with partial coarse aggregate replacement with recycled plastic are examined in this section. However, many researchers observed the compressive strength of concrete decreased as the percentage of replacement of coarse aggregate with waste plastic increased. In some cases, the compressive strength increased as more aggregate was replaced with plastics. The research documents are ordered from oldest to newest in date.

Ghaly and Gill (2004)

Ghaly and Gill (2004) examined different plastic replacement amounts and different w/c ratios in order to study the compressive strength of concrete with plastic aggregates. Ghaly and

Gill replaced coarse aggregates in concrete with 5%, 10%, and 15% plastics with w/c ratios of 0.42, 0.54, and 0.69. The type of plastics used for these tests was not stated and the exact concrete mix was not given. A total of 198 cube specimens were prepared and tested without a standard stated. For each w/c ratio a total of 66 cubes were prepared and were grouped based on age and percentage of plastic replacements. The maximum size of aggregate used was 9.5 mm (0.37 inch) because the molds used were 50.8 mm (2 inch) cubes and using larger particles sizes is not suitable for a mold this small. The specimens were loaded to failure using a constant loading rate and the average of each group was recorded. Ghaly and Gill stated that the specimens containing plastic aggregates failed at a lower compressive load as compared to the specimens with only conventional concrete. The specimens underwent considerable deformation and did not experience brittle failure, despite the lower compressive loads. The percent reduction in the 28-day compressive strength is shown in Table 3.2. The results also indicated that with the increase of the w/c ratio the compressive strength decreased, which is also the case in concrete containing just natural aggregates. Ghaly and Gill concluded that concrete with plastic aggregate replacement is useful in applications requiring non-load bearing concrete, such as concrete panels used in facades.

Table 3.2 Ghaly and Gill (2004) Percent Reduction in Compressive Strength

	Percent reduction in compressive strength		
% plastics	w/c = 0.42	w/c = 0.54	w/c = 0.69
0	0	0	0
5	14.75	6.37	15.17
10	18.04	20.37	18.65
15	28.64	29.28	34.78

Saikia and De Brito (2012)

Saikia and De Brito (2012) is the second research presented here. They conducted a study to analyze the effects of PET plastic replacement as aggregate in concrete. They collected plastic from a plastic recycling plant and Portugal which had a system already in place to prepare the plastics, so no further work was required by the researchers in their laboratory. Three subclasses of concrete were created by replacing 5%, 10%, and 15% of natural aggregate with recycled PET aggregate. The test method used for compressive strength was EN 12390-3 using cylindrical specimens and w/c ratios of 0.53 for the control group, 0.61 for 5% replacement, 0.65 for 10% replacement, and 0.74 for 15% replacement. The concrete mixes are shown in Table 3.3. To maintain slump, the w/c ratio was increased as the percentage of replacement increased. The results were as expected with the compressive strength decreasing as the percentage of replacement of aggregate with PET increased. A 27% decrease for 5% replacement, 47% decrease for 10% replacement, and a 65% decrease for 15% replacement for the 28-day compressive strength occurred. A slight increase in the first 7 days was recorded, possibly resulting from the low thermal conductivity of the PET aggregate. High w/c ratios were being used in this research, so it was not a surprise the compressive strength decreased significantly as the replacement increases. Saikia and De Brito concluded that only 5% replacement of coarse aggregate with PET aggregate would be reasonable as higher replacement resulted in insufficient compressive strength.

Table 3.3 Saikia and De Brito (2012) Concrete Mix

			Aggregate kg/m ³ (lb/ft ³)		
Concrete Mixes	Cement kg/m ³ (lb/ft ³)	Water kg/m ³ (lb/ft ³)	Coarse	Fine	PET
Ref	350 (21.8)	185.5 (11.6)	996.4 (62.2)	802.7 (50.1)	0
PC5	350 (21.8)	213.5 (13.3)	920.4 (57.4)	788.4 (49.2)	45.9 (2.8)
PC10	350 (21.8)	227.5 (14.2)	844.4 (52.7)	774.1 (48.3)	91.7 (5.7)
PC15	350 (21.8)	259 (16.2)	768.5 (48)	759.8 (47.4)	137.5 (8.6)

Prasanna and Rao (2014)

Prasanna and Rao (2014) conducted an experimental study to utilize E-plastic in concrete. The coarse aggregate was replaced with 5%, 10%, 15%, and 20% of 10 mm to 20 mm (0.4 inch to 0.8 inch) E-plastic particles. Prasanna and Rao did not provide a concrete mix design. No test method was specified but the location of the study was in India, so it is assumed that Prasanna and Rao tested the specimens for compression using cube samples as per IS 516. The w/c ratio was also not included, and neither was the concrete mix. Prasanna and Rao recorded 28-day compressive strengths that were 89%, 79%, 75%, and 66% of the compressive strength containing only natural coarse aggregate for the 5%, 10%, 15%, and 20% replacements, respectively. Besides stating that the compressive strength of the concrete decreased as the plastic replacement increased, no other conclusions or recommendations were given.

Akram, Sasidhar, and Pasha (2015)

Akram, Sasidhar, and Pasha (2015) conducted tests to compare the compressive strength of concrete containing plastic coarse aggregates to conventional concrete. A total of 72 cube

samples were tested for compression strength as per IS 516. The concrete mix was not provided. All the samples had a w/c ratio of 0.5 and were grouped by the percentage of replacement of E-Plastic; 5%, 10%, and 15%. The E-plastic waste size used was 20 mm (0.8 inch) replacing the coarse aggregate in the given percentages. The results indicated the compressive strength decreased as the percentage of replacement increased. The average reduction in the 28-day compressive strength for 15% plastic replacements was stated as 34%. Akram et al. concluded that this reduction is most likely due to the decrease in adhesive strength between the cement paste and the plastic aggregates.

Manjunath (2016)

Manjunath (2016) conducted an experimental study on the utilization of E-plastic waste as coarse aggregate in concrete with a percent replacement ranging from 10%, 20%, and 30% on the strength of concrete. The concrete mix design was not provided. The size of the coarse aggregate ranged between 12.5 mm (0.5 inch) and 20 mm (0.8 inch) in length with a thickness ranging from 2 mm (0.08 inch) to 8 mm (0.3 inch). The concrete was hand mixed with a w/c ratio of 0.5 and the specimens were tested in 150 mm (5.9 inch) cubes, 150 mm (5.9 inch) x 300 mm (11.8 inch) cylinders, and 150 x 150 x 300 mm (5.9 x 5.9 x 11.8 inch) beams as per IS 516. A 6.6% decrease for 10% replacement, 47% decrease for 20% replacement, and a 53% decrease for 30% replacement for the 28-day compressive strength occurred. The results indicated a common trend that shows as the plastic replacement increases the compressive strength decreases. Manjunath concluded that these values decreased below the reference concrete mixtures, and this was possibly due to decrease in adhesive strength between the materials.

Shamnugapriya and Santhi (2017)

Shamnugapriya and Santhi (2017) conducted tests on the compressive strength of concrete by replacing coarse aggregate with 10%, 15%, and 20% HDPE plastics with a 0.42 w/c ratio. The maximum size of aggregate used was 12.5 mm (0.5 inch) along with ordinary Portland cement in the concrete mix. The mix designation is shown in below in Table 3.4 and the mixes, C1, C2, and C3, represent the replacement of coarse aggregate with 10%, 15%, and 20% HDPE plastics, respectively. A compressive test was conducted on various 150 mm (5.9 inch) cube samples as per IS 516 and resulted in a lower compressive strength than that only containing natural aggregates. The 28-day compressive strength with 10%, 15%, and 20% of plastic coarse aggregate decreased by 18%, 1%, and 16%, respectively. Here, the concrete with the 15% replacement showed the most comparable results to the concrete with only natural aggregates with only a slight decrease in the compressive strength compared to the concrete with natural aggregates only. Overall, the strength does decrease, and this could be due to the low bond strength between the cement paste and the surface of the plastic as well as the hydrophobic nature of the plastic which restricts the movement of water.

Table 3.4 Shamnugpriya and Santhi (2017) Concrete Mix

Mix Designation	Quantity in kg/m ³ (lb/ft ³)			
	Cement	Fine aggregate	Coarse aggregate	HDPE*
CC	320 (20)	848.8 (53)	1286.5 (80.3)	0
C1	320 (20)	848.6 (53)	1157.86 (72.3)	128.68 (8)
C2	320 (20)	848.6 (53)	1093.55 (68.27)	192.99 (12)
C3	320 (20)	848.6 (53)	1029.23 (64.25)	257.31 (16.06)
*HDPE = HDPE plastic aggregate.				

Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017)

Tamang et al. (2017) conducted tests to compare the compressive strength of concrete with natural aggregate to the compressive strength of a similar concrete mix that had partial replacement of coarse aggregate with PET plastic. Tamang et al. used a w/c ratio of 0.45 with 10%, 15%, and 20% replacements of coarse aggregate. The mix quantities are shown in Table 3.5 with sand and cement staying constant for all samples and the natural coarse aggregate being partially replaced with PET plastic. Over eighty 150 x 150 x 150 mm (5.9 x 5.9 x 5.9 inch) cube-samples were casted and subjected to a compression test as per IS 516. After taking the average of the samples, the compressive strength at 28 days showed no significant decreases compared to the control group with only natural aggregates. Surprisingly, Tamang et al. concluded that the concrete with 20% replacement gave the highest compressive strength with only a 2% decrease from the control group compared to the other replacement percentages. No discussion or reasoning was given as to why the highest percentage of replacement resulted in the highest compressive strength.

Table 3.5 Tamang et al. (2017) Concrete Mix Quantities of Solids

No.	Material	Weight	
		kg	lbs
1	Cement	413.33	911.24
2	Sand	662.68	1460.95
3	Coarse aggregate	1309.8	2887.6

Needhidsan, Ramesh, and Prabu (2020)

Needhidsan, Ramesh, and Prabu (2020) wanted to find a use for the increased amount of electronic plastic waste from the disposal of various types of electronic devices. Inspired by previous research on this, Needhidsan et al. decided to conduct their own study on the compressive strength of concrete containing plastic aggregates. 20 mm (0.8 inch) E-plastic particles were used to replace 10% and 12.5% of coarse aggregate in concrete with a w/c ratio of 0.5. The design mix of the concrete was not provided. A series of tests for the compressive strength of concrete were carried out as per IS 516 using 150 mm (5.9 inch) cubes. The sample with 10% E-plastic coarse aggregate resulted in a 28-day compressive strength that only decreased by 1% compared to the compressive strength of the control group tested, while the 12.5% replacement decreased by 14%. Needhidsan et al. concluded that as the percentage of E-plastic waste increases, the compressive strength decreases due to the smooth surface of the E-plastic waste. Needhidsan et al. determined that since the compressive strength only decreased by 1% and 14%, for the 10% and 12.5% replacements, the decrease in strength was acceptable.

Costello (2021)

Costello (2021) conducted research to observe the fresh and hardened properties of concrete after partial replacement of coarse aggregate using an extruded recycled ocean plastic waste product called Plazrok which was developed by the company Enviroplaz. The coarse aggregate was replaced with Plazrok in percentage of 15%, 30%, and 45% with a w/c ratio of 0.45. Costello's concrete mix design is provided in Table 3.6. The concrete cylindrical specimens were cast and tested for compression as per ASTM C39. A proportional decrease in compressive strength as the rate of replacement of the aggregate increased occurred. The 28-day compressive strength of the concrete decreased by 19.1%, 35.9%, and 48.1% for the replacement percentages of 15%, 30%, and 45%, respectively. Costello concluded that "a significant influence of the incorporation of Plazrok on the strength development other than the decrease in strength." Costello was the only author that used the ASTM method to determine the compressive strength of concrete using cylindrical specimens, while other authors used the IS cube method. As discussed in section 3.1.2, the cylinder to cube ratio ranges between 0.65 to 0.9. The average of this ratio is 0.78. In order to get a more accurate comparison between the authors, Costello's compressive strength results were divided by this ratio. Table 3.7 shows Costello's results before and after dividing by the cylinder/cube ratio.

Table 3.6 Costello (2021) Concrete Mix

Mix	Cement kg (lbs)	Fine Agg. kg (lbs)	Coarse Agg. kg (lbs)	Water kg (lbs)	Plazrok kg (lbs)
Control	47.4 (104.5)	170 (375)	94 (207)	21.3 (46.9)	0
15% Replacement	47.4 (104.5)	170 (375)	80.3 (170)	21.3 (46.9)	3.8 (8.4)
30% Replacement	47.4 (104.5)	170 (375)	66.1 (145.7)	21.3 (46.9)	7.6 (18.2)
45% Replacement	47.4 (104.5)	170 (375)	51.9 (114.5)	21.3 (46.9)	11.6 (25.2)

Table 3.7 Costello (2021) Compressive Strength Results

	Cylinder Specimen Compressive Strength		Compressive Strength after Cylinder/Cube ratio	
Days	fc MPa (psi)	Control fc MPa (psi)	fc MPa (psi)	Control fc MPa (psi)
7	30.5 (4423.6)	37 (5366.4)	39.1 (5671.0)	47.4 (6874.8)
14	32.4 (4699.2)	41 (5961)	41.5 (6019.1)	52.7 (7643.5)
28	36.3 (5264.9)	44 (6425.2)	46.5 (6744.3)	56.8 (8238.1)

3.1.4 Comparison of Compressive Strength Test Results

Due to the varying results discussed, several tables and graphs are created to showcase possible trends between partial plastic replacement as coarse aggregate and compressive strength of concrete. The graphs are divided based on the percentage of plastic replacement: 10%, 15%, and 20%. Since less stone aggregate replacement correlates with less compressive strength reduction, more tests with a 10% and 15% recycled plastic aggregate replacement occurred. Due to the amount of these tests, the 10% and 15% replacement test results were divided based on their w/c ratios. The tables include the name of the author along with the year the tests were

conducted, the w/c ratios, the type of plastic used, the resulting compressive strength, the corresponding control compressive strength, and the percentage of decrease in compressive strength after replacement. The tables are ordered from the smallest to largest w/c ratios. The graphs are made based on the resulting compressive strength after the replacement versus curing days. The average decrease for a 10% replacement was 19.7%, the average decrease for a 15% replacement was 23%, and the average decrease for a 20% replacement was 24.4%. Using these averages, Eq 3.4 was created as an estimate to determine the compressive strength of concrete after plastic replacement. Because this equation had to satisfy all three percentages of replacement, it is not a perfect equation but rather a close estimate.

$$f_{c \text{ replacement}} = \frac{100 - (r + 7)}{100} f_c \quad \text{Eq. 3.4}$$

where:

$f_{c \text{ replacement}}$ = resulting compressive strength;

f_c = compressive strength of control mix;

r = percent of plastic replacement.

Table 3.8 summarizes the test results of the compressive strength of concrete with 10% replacement of coarse aggregate with w/c ratios ranging from 0.4-0.5. The solid lines indicate the control mixes with no replacement and the dashed lines indicate the compressive strength after the replacement. The highest compressive strength results were achieved by Ghaly and Gill (2004) cube test specimens with a w/c ratio of 0.42 and an unspecified type of plastic waste. From all the results given, the w/c ratio had little effect on the compressive strength of concrete with plastic replacement. Akram et al. (2015) cube test specimens, with a w/c ratio of 0.5, had the largest decrease in compressive strength at the 28-day mark; with plastic replacement being

63% than that of conventional concrete. But Needhidsan et al. (2020) cube specimens with a w/c ratio of 0.5 had little decrease in strength with the 28-day compressive strength of the concrete with plastic being 99% of the conventional concrete. Other authors, like Shamnugapriya and Santhi (2017), Tamang et al. (2017), and Prasanna and Rao (2014), cube tests had comparable results with their 28-day compressive strength of concrete with replacement ranging from 79%-92% of the compressive strength of their conventional concrete, respectively. The results from Table 3.8 are further analyzed by graphing the resulting compressive strength versus curing days as shown in Figure 3.4. As depicted in Figure 3.4, most of the resulting compressive strength are close together in range with Ghaly and Gill's (2004) results being an outlier showing higher results than the rest.

Table 3.8 Compressive Strength with 10% Replacement (0.4-0.5 w/c)

Source	Days	w/c	Replacement	fc (MPa)	fc (psi)	Control fc (MPa)	Control fc (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	10% HDPE	22.5	3263.3	24.1	3495.4	6.6
	14	0.42	10% HDPE	24.2	3509.9123	28	4061.1	13.6
	28	0.42	10% HDPE	28.2	4090.0631	35	5018.3	18.5
Ghaly and Gill (2004)	7	0.42	10%	34.3	4974.8	44.6	6464.3	23.0
	14	0.42	10%	40.1	5816.0	44.9	6506.4	10.6
	28	0.42	10%	50.1	7266.3888	61	8861.8	18.0
Tamang et al. (2017)	7	0.45	10% PET	16.59	2406.2	17.7	2570.1	6.4
	14	0.45	10% PET	19.88	2883.3	22.1	3208.2	10.1
	28	0.45	10% PET	21.58	3129.9	23.4	3391.0	7.7
Akram et al. (2015)	7	0.5	10% E-Plastic	13.5	1958.0	15.7	2277.1	14.0
	14	0.5	10% E-Plastic	15.0	2175.6	22.0	3190.8	31.8
	28	0.5	10% E-Plastic	17.6	2552.7	28.0	4061.1	37.1
Manjunath (2016)	7	0.5	10% E-Plastic	33.18	4812.4	36.0	5221.4	7.8
	14	0.5	10% E-Plastic	41.25	5982.8	44.8	6499.1	7.9
	28	0.5	10% E-Plastic	44.07	6391.8	47.2	6842.9	6.6
Needhidasan et al. (2019)	7	0.5	10% E-Plastic	16.4	2378.6183	16.1	2336.6	-1.8*
	14	0.5	10% E-Plastic	23.5	3408.386	25.0	3625.9	6.0
	28	0.5	10% E-Plastic	27.7	4017.5443	28.0	4061.1	1.1
*A negative sign indicates an increase in strength.								

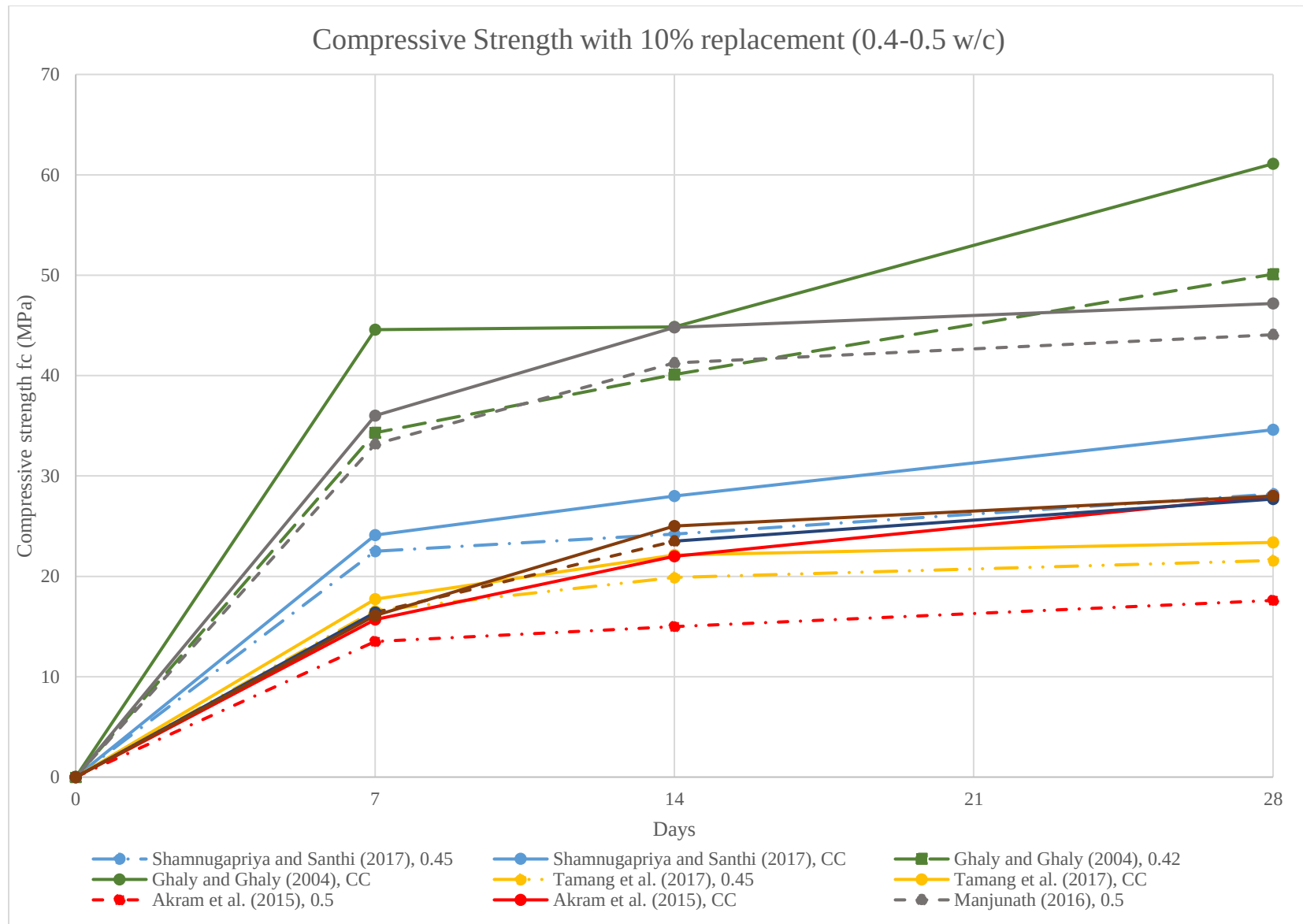


Figure 3.4 Compressive Strength with 10% Replacement (0.4-0.5 w/c)

The next set of results grouped together are the experiments with 10% replacement of coarse aggregate with w/c ratios ranging from 0.51-0.7. The results shown in Table 3.9 are graphed indicate a common trend with all the resulting compressive strengths decreasing after the partial replacement. Manjunath (2016) cube tests, who had a w/c ratio of 0.55, had the best results with the 28-day compressive strength of the concrete with plastic replacement being 93% of the compressive strength of the conventional concrete. While each result depends on the specific mix design, a common concept is that as the w/c ratio increases the compressive strength will decrease. This is shown in Saikia and De Brito (2012) cube test results with a 0.65 w/c ratio and a decrease in strength by almost 50%. Ghaly and Gill (2004) cube tests had two results in this table, a 0.54 w/c ratio, and a 0.69 w/c ratio that showed comparable results to their corresponding conventional concrete. However, as seen from the previous Table 3.8, Ghaly and Gill (2004) had the highest results; so overall Ghaly and Gill (2004) had a very high resulting compressive strength compared to other authors but not much was discussed about the specific mix design used and why the results were so high. This is why Ghaly and Gill's (2004) results with the w/c ratio of 0.69 had a higher resulting 28-day compressive strength compared to Saikia and De Brito (2012). A high w/c ratio is not recommended as it will decrease the strength and workability of concrete. Figure 3.5 indicates the resulting compressive strength versus curing days.

Table 3.9 Compressive strength with 10% replacement (0.51-0.7 w/c)

Source	Days	w/c	Replacement	fc (MPa)	fc (psi)	Control fc (MPa)	Control fc (psi)	% Decrease
Ghaly and Gill (2004)	7	0.54	10%	29.4	4264.1	41.2	5975.6	28.6
	14	0.54	10%	36.3	5264.8685	50.0	7251.9	27.4
	28	0.54	10%	40.8	5917.5382	51.2	7425.9	20.3
Saikia and De Brito (2012)	7	0.65	10% PET	18.25	2646.9	33.2	4812.4	45.0
	14	0.65	10% PET	20	2900.8	37.0	5366.4	45.9
	28	0.65	10% PET	22.42	3251.7452	43.1	6246.8	47.9
Ghaly and Gill (2004)	7	0.69	10%	22.6	3277.9	32.3	4684.7	30.0
	14	0.69	10%	26.8	3887.0	33.4	4844.3	19.8
	28	0.69	10%	30.2	4380.1	37.2	5395.4	18.8
Prasanna and Rao (2014)	7	-	10% E-Plastic	17.47	2533.8086	24.1	3501.2	27.6
	14	-	10% E-Plastic	26.47	3839.1479	33.6	4873.3	21.2
	28	-	10% E-Plastic	32.29	4683.2673	40.9	5929.1	21.0

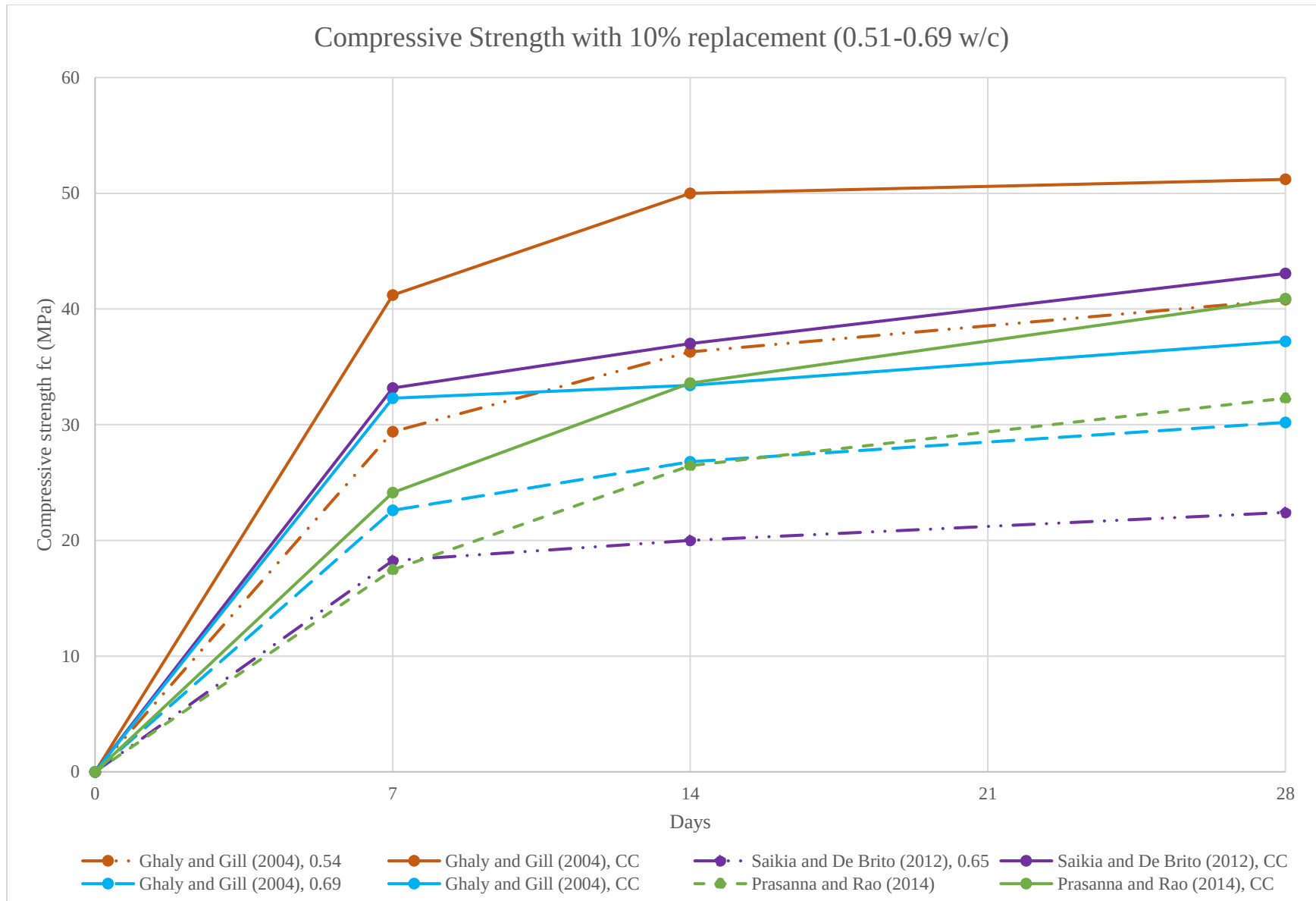


Figure 3.5 Compressive Strength with 10% Replacement (0.51-0.7 w/c)

Due to the number of tests, the 15% replacement test results were divided based on their w/c ratios. Table 3.10 and Figure 3.6 include w/c ratios ranging from 0.42-0.5, and Table 3.11 and Figure 3.7 include w/c ratios ranging from 0.51-0.74. As shown in the tables, all the resulting compressive strength from the authors showed a decrease in strength which is what would be expected. Saikia and De Brito (2012) had the highest decrease with the 28-day compressive strength after replacement being only 35% of the conventional concrete. This value was removed from the average because it had such a high decrease compared to the other tests. A reason for this might be the very high w/c ratio used, which was 0.74. Akram also had incomparable results with the resulting 28-day compressive strength decreasing by a little over 40%. In contrast, Shamnugapriya and Santhi (2017) and Tamang et al. (2017) had the best resulting 28-day compressive strength with only a 1% and a 5% decrease, respectively. The rest of the authors, Ghaly and Gill (2004), Costello (2021), and Prasanna and Rao (2014) had resulting 28-day compressive strength that decreased in the range of 20%-30% from their conventional concrete. These results were considered comparable and recommended for non-load bearing elements as discussed in section 3.1.3 of this thesis. In the corresponding figures for the tables, these results varied and are not close together in range which, again, depends on each experiment specific mix design and other factors such as preparation and testing method.

Table 3.10 Compressive Strength with 15% Replacement (0.42-0.5 w/c)

Source	Days	w/c	Replacement	fc (MPa)	fc (psi)	Control fc (MPa)	Control fc (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	15% HDPE	24.8	3596.9	24	3495.4	-3*
	14	0.42	15% HDPE	26.1	3785.5	28	4061.1	7
	28	0.42	15% HDPE	34.2	4960.3	35	5018.3	1
Ghaly and Gill (2004)	7	0.42	15%	30.3	4394.6	45	6468.7	32
	14	0.42	15%	37.6	5453.4	45	6512.2	16
	28	0.42	15%	43.6	6323.6	61	8861.8	29
Tamang et al. (2017)	7	0.45	15% PET	16.46	2387.3	18	2570.1	7
	14	0.45	15% PET	20.64	2993.6	22	3208.2	7
	28	0.45	15% PET	22.11	3206.8	23	3391.0	5
Costello (2021)	7	0.45	15% Plazrok	39.1	5671.0	47	6874.8	18
	14	0.45	15% Plazrok	41.5	6019.1	53	7643.5	21
	28	0.45	15% Plazrok	46.5	6744.3	57	8238.1	18
Akram et al. (2015)	7	0.5	15% E-Plastic	12.1	1755.0	16	2277.1	23
	14	0.5	15% E-Plastic	14	2030.5	22	3190.8	36
	28	0.5	15% E-Plastic	15.8	2291.6	28	4061.1	44
*A negative sign indicates an increase in strength.								

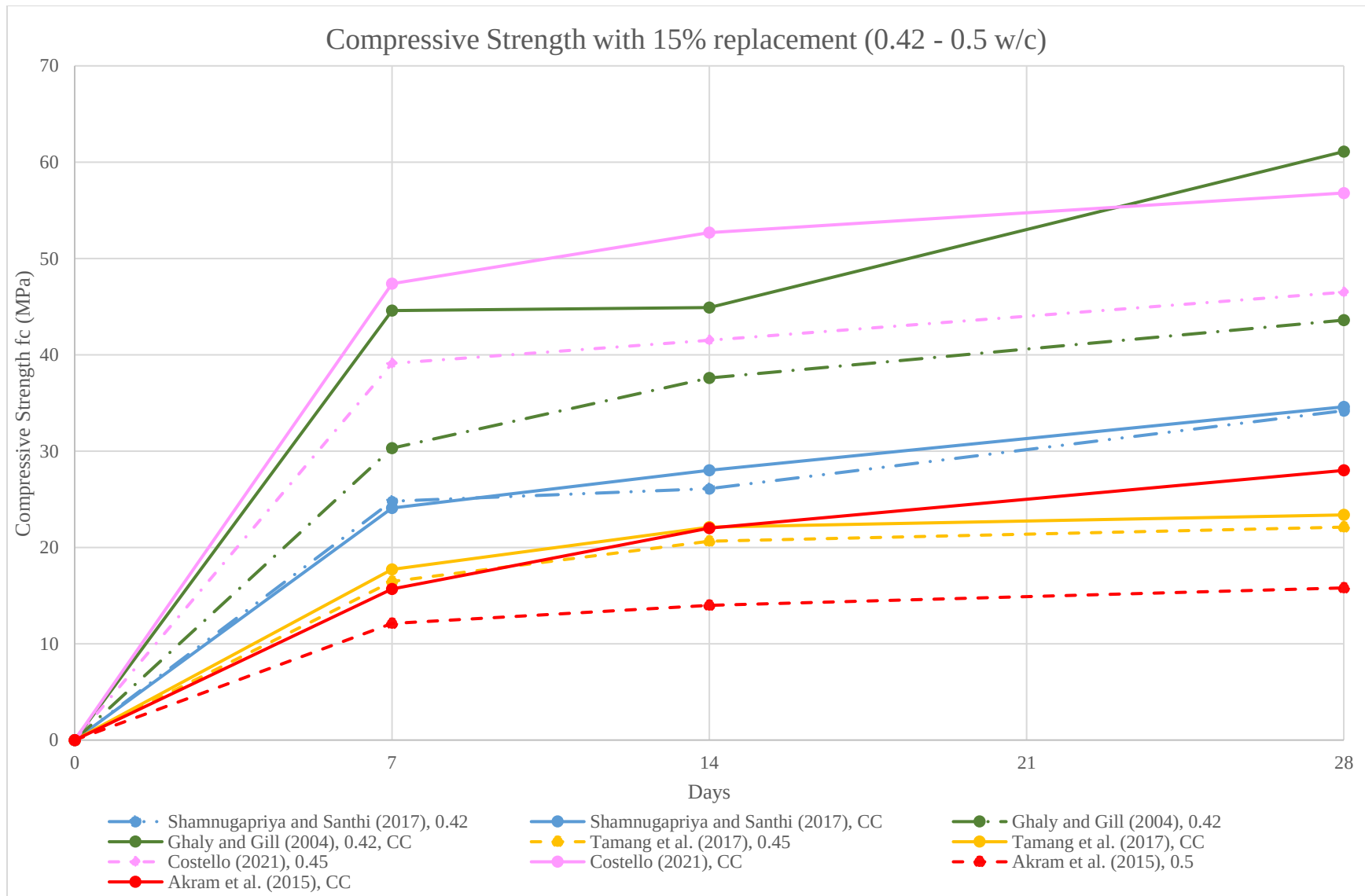


Figure 3.6 Compressive Strength with 15% Replacement (0.42-0.5 w/c)

Table 3.11 Compressive Strength with 15% Replacement (0.51-0.74 w/c)

Source	Days	w/c	Replacement	fc (MPa)	fc (psi)	Control fc (MPa)	Control fc (psi)	% Decrease
Ghaly and Gill (2004)	7	0.54	15%	26.1	3785.5	41	5975.6	37
	14	0.54	15%	32.5	4713.7	50	7251.9	35
	28	0.54	15%	36.2	5250.4	51	7425.9	29
Ghaly and Gill (2004)	7	0.69	15%	19.5	2828.2	32	4684.7	40
	14	0.69	15%	20.8	3016.8	33	4844.3	38
	28	0.69	15%	24.3	3524.4	37	5395.4	35
Saikia and De Brito (2012)	7	0.74	15% PET	11.2	1624.4	33	4812.4	66
	14	0.74	15% PET	12	1740.5	37	5366.4	68
	28	0.74	15% PET	15.1	2190.1	43	6246.8	65
Prasanna and Rao (2014)	7	-	15% E-Plastic	15.92	2309.0	24	3501.2	34
	14	-	15% E-Plastic	25.2	3655.0	34	4873.3	25
	28	-	15% E-Plastic	30.51	4425.1	41	5929.1	25

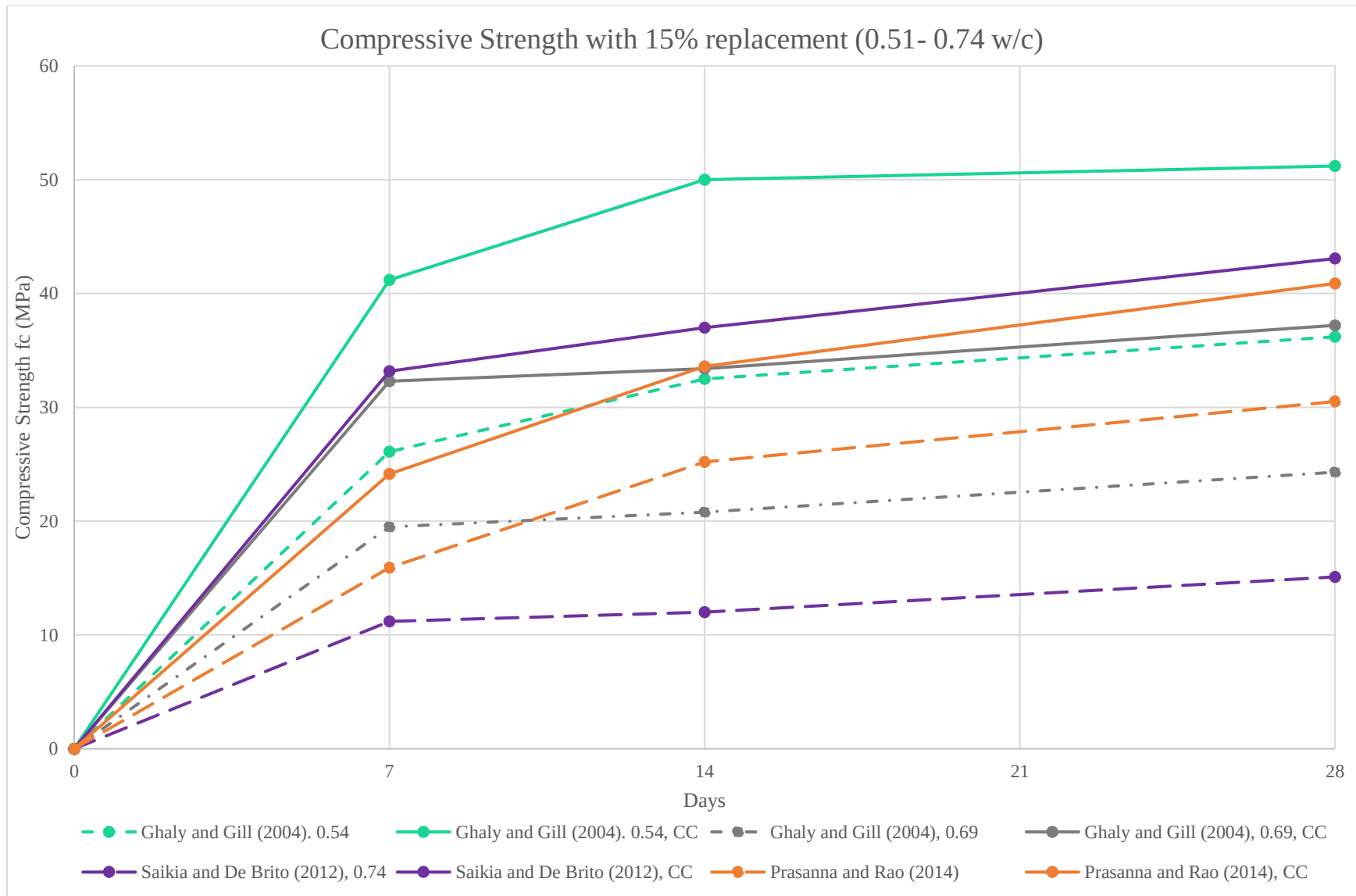


Figure 3.7 Compressive Strength with 15% Replacement (0.51-0.74 w/c)

The last set of results is the compressive strength of concrete with 20% plastic replacement of coarse aggregate. As shown in Table 3.12, the results varied, and a common trend does not occur. Manjunath (2016), who had a w/c ratio of 0.55, also had a very high decrease in strength with the 28-day compressive strength with plastic replacement being 54% of the conventional concrete, and a sudden decrease in strength after 14 days which was not discussed. Prasanna and Rao (2014) had a resulting 28-day compressive strength that was 66% than that of conventional concrete which could be deemed unfavorable. In contrast, Tamang et al. (2017) had the best results here with the 28-compressive strength with plastic replacement only decreasing by 2%. Shamnugapriya and Santhi (2017) had results that were expected with the resulting 28-day compressive strength decreasing by about 25%. Figure 3.8 graphs the resulting compressive strengths from Table 3.12 versus curing days.

Table 3.12 Compressive Strength with 20% Replacement

Source	Days	w/c	Replacement	fc (MPa)	fc (psi)	Control fc (MPa)	Control fc (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	20% HDPE	21	3045.8	24.1	3495.4	12.9
	14	0.42	20% HDPE	23.8	3451.9	28.0	4061.1	15.0
	28	0.42	20% HDPE	29	4206.1	34.6	5018.3	16.2
Tamang et al. (2017)	7	0.45	20% PET	15.8	2291.6	17.7	2570.1	10.8
	14	0.45	20% PET	17.1	2480.1	22.1	3208.2	22.7
	28	0.45	20% PET	22.87	3317.0	23.4	3391.0	2.2
Manjunath (2016)	7	0.55	20% E-Plastic	19.9	2886.3	36.0	5221.4	44.7
	14	0.55	20% E-Plastic	17.95	2603.4	44.8	6499.1	59.9
	28	0.55	20% E-Plastic	25.7	3727.5	47.2	6842.9	45.5
Prasanna and Rao (2014)	7	-	20% E-Plastic	14.66	2126.3	24.1	3501.2	39.3
	14	-	20% E-Plastic	23.7	3437.4	33.6	4873.3	29.5
	28	-	20% E-Plastic	27.1	3930.5	40.9	5929.1	33.7

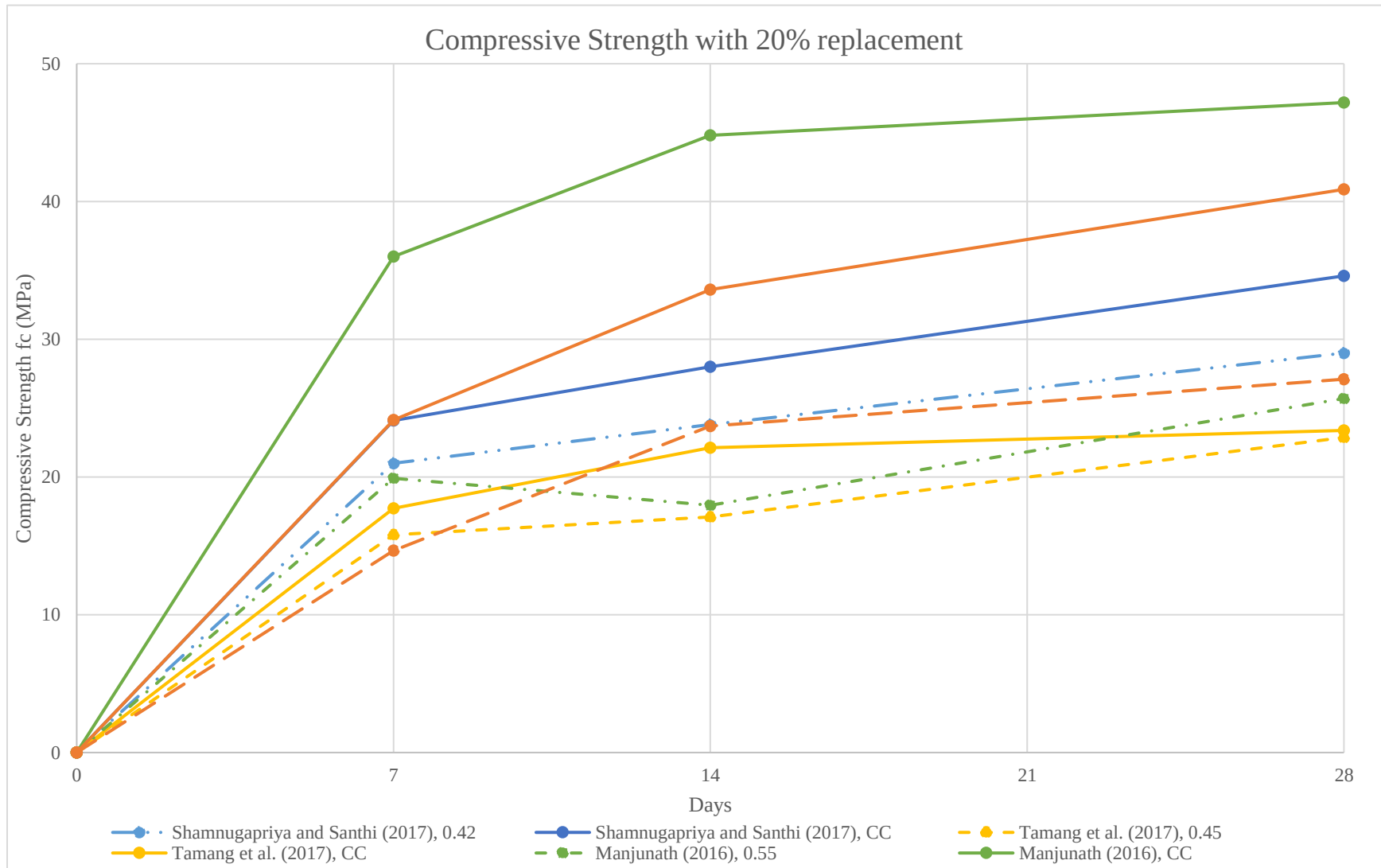


Figure 3.8 Compressive Strength with 20% Replacement

3.2 Splitting Tensile Strength

3.2.1 Importance of Splitting Tensile Strength

Compressive and split tensile are the most essential properties of concrete. Since the direct tensile test is difficult to perform and the results are unreliable, indirect tensile strength tests, split tensile strength and flexural strength tests are performed to determine the tensile strength of concrete (Chhorn et al., 2018). Concrete is a brittle material, weak in tension, making concrete develop cracks easily. When the tensile forces on the concrete exceed its tensile strength, cracks develop, and the concrete will fail in tension. Variations in water to cement ratio, ingredient proportioning, and increase in slump will impact the strength of concrete. Split tensile strength is one of the crucial properties of concrete and is used to design structural elements of concrete subjected to transverse shear, torsion, shrinkage, etc. (IS 5816:1999). Therefore, it is important to conduct tests to determine the tensile strength of concrete and the load at which the concrete will crack. As used in concrete codes and standards, square root functions are used mostly to find tensile strength from compressive strength (f_c) (ACI 381-19). The tensile strength of concrete approximately equals 10% of compressive strength; therefore, reinforcing steel is used to carry the tension forces within structural members (Splitting Tensile Strength of Concrete – Civil Engineering Forum, 2017). Since the splitting tensile strength of concrete is roughly 10% of the compressive strength, it typically ranges from 2.5 MPa to 4 MPa (360 psi to 580 psi). The main objectives of the splitting tensile strength test are to determine the tensile strength of concrete, to determine the uniform stress distribution, and to study the behavior of concrete.

3.2.2 Test Methods to Determine Splitting Tensile Strength

Two main methods are used widely to determine the splitting tensile strength of concrete. The first method for concrete tensile strength utilizes the American Society of the International Association for Testing and Materials (ASTM) standards. ASTM C496 *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* provides a step-by-step procedure for determining the splitting tensile strength of concrete on cylindrical concrete samples such as molded cylinders and drilled cores. Molded cylinders are typically used for research since fresh concrete is tested. Drilled cores are used for existing concrete structures to determine in-place strengths. Both types of specimens are tested similarly. The ASTM C496 method consists of applying a diametral compressive load along the length of a cylindrical concrete sample at a continuous rate until failure occurs. It is instructed that a supplementary bearing bar or plate of machined steel is to be used if the diameter or the largest dimension of the upper bearing face or the lower bearing block is less than the length of the cylinder to be tested. This bearing bar must be at least 2 in. (50 mm) wide and have a thickness no less than the distance from the edge of the spherical or rectangular bearing block to the end of the cylinder. The bar or plate is placed in such manner that the load is applied over the entire length of the specimen. Two bearing strips of nominal 1/8 in. (3.2 mm) thick plywood that is an inch (25 mm) wide and a length equal to or slightly longer than the specimen are used. These bearing strips are placed between the specimen and both the upper and lower bearing blocks of the testing machine and should not be reused. One of the plywood strips is centered along the center of the lower bearing block and the specimen is placed on the plywood strip and aligned with the center of it, the second plywood strip is centered along the length of the cylinder. The cylindrical specimen is then placed in the testing machine and continuous loading is applied. When the force indicator

on the testing machine shows the load decreasing steadily, the load is stopped. The maximum load carried by the sample is recorded and divided by the appropriate geometrical factors to determine the splitting tensile strength. The loading applied induces tensile stresses on the same plane the load is being applied which causes tensile failure of the cylindrical sample. Tensile failure occurs before compressive failure in this method since the areas of load application are in a state of triaxial compression. This allows the sample to withstand much higher compressive stresses and fail in tension first. The splitting tensile strength is calculated using Eq. 3.5 (ASTM C496).

$$T = \frac{2P}{\pi l D} \quad \text{Eq. 3.5}$$

where:

T = splitting tensile strength, MPa (psi);

P = maximum applied load indicated by the testing machine, N (lbf);

l = length, mm (in);

D = diameter, mm (in).

The second common method used for determining the splitting tensile strength of concrete utilizes the Indian standards. IS 5816-1999 *Splitting Tensile Strength of Concrete – Method of Test* provides a procedure to test the tensile strength of concrete by using cylindrical samples. Similar to the ASTM C496 procedure, a load is applied to the cylindrical specimen at a constant rate until failure. The maximum load is recorded and divided by the appropriate geometrical factors to determine the splitting tensile strength. This method utilizes the same equation for the splitting tensile strength as the ASTM C496 method which is given above (IS 5816-1999).

3.2.3 Splitting Tensile Strength of Concrete After Plastic Replacement

Studies and research on the splitting tensile strength of concrete with plastic aggregate as coarse aggregate have been conducted. Seven research documents with partial coarse aggregate replacement with recycled plastic, ordered from oldest to newest in date, are examined in this section. A possible common trend is for the splitting tensile strength to decrease as the plastic content in the concrete increases. However, this was not the case in all the tests conducted due to varying reasons discussed for each study examined. Only new information from the research studies is given in this section. The number of tests and concrete mix information is given in the compressive test section of this thesis.

Prasanna and Rao (2014)

Prasanna and Rao (2014) conducted a study to the coarse aggregate in concrete with 5%, 10%, 15%, and 20% of E-plastic particles. No test method was specified but the location of the study was in India; therefore, it is assumed Prasanna and Rao tested the specimens for tension using cylinders as per IS 5816. The 28-day splitting tensile strength showed a consistent decrease as the E-plastic replacement increased. The results showed the splitting tensile strength was 97% of the conventional concrete for the 5% replacement, 92% for the 10% replacement, 88% for the 15% replacement, and 40% for the 20% replacement. No conclusion discussing these results and causes was given. However, this decrease in the splitting tensile strength is acceptable as it gradually decreases as the replacement increases.

Akram, Sasidhar, and Pasha (2015)

Akram, Sasidhar, and Pasha (2015) prepared samples of concrete with replacement of coarse aggregate with E-Plastic aggregate in percentage of 5%, 10%, and 15%. 72 samples with a w/c ratio of 0.5 were tested for splitting tensile strength as per IS 5816. The 28-day splitting tensile strength with 5% replacement was slightly higher than the splitting tensile strength of the control concrete. Akram et al. stated that this could be due to the control specimen having brittle type failure, sudden breakage accompanied by sound, in contrast to the specimens containing E-plastic, which had smooth failures without any noise during breakage. This indicated the addition of E-plastic aggregated can induce ductility into the concrete if added in proper proportions. The 28-day splitting tensile strength of the specimen containing 10% E-plastic was 89% of the control concrete while the splitting tensile strength of the specimen containing 15% E-plastic was 84% of the control concrete. Akram et al. concluded the decrease for the 10% and the 15% replacement was likely due to the poor bond strength between the E-plastic aggregate and the cement paste.

Manjunath (2016)

Manjunath (2016) utilized E-plastic waste as coarse aggregate in concrete with a percent replacement ranging from 10%, 20%, and 30%. The concrete had a w/c ratio of 0.5. A 300 mm x 150 mm (11.8 inch x 5.9 inch) cylinder was used, and the specimens were tested for splitting tensile strength in accordance with IS 5816. The 28-day splitting tensile strength was 98% of the control concrete for the 10% replacement, 110% for the 20% replacement, and 77% for the 30% replacement. No further information was provided by Manjunath as to why the 20% replacement had a 10% increase in strength and the sudden decrease for the 30% replacement.

Since the 20% was the only one showing an increase in the splitting tensile strength, this most likely occurred to human error during the testing process.

Shamnugapriya and Santhi (2017)

Shamnugapriya and Santhi (2017) conducted tests on the splitting tensile strength of concrete by replacing coarse aggregate with 10%, 15%, and 20% HDPE plastics with a 0.42 w/c ratio. Refer to Table 3.4 for concrete mix design information. The splitting tensile test was conducted in accordance to IS 5816 using 150 mm x 300 mm (5.9 inch x 11.8 inch) concrete cylinders. The results showed the 7-day splitting tensile strength of the specimens containing HDPE plastics was higher than the conventional concrete sample, possibly due to the ductile property of the HDPE waste. However, the 28-day splitting tensile strength of the specimens containing HDPE waste was lower than the conventional concrete. Shamnugapriya and Santhi recorded compressive strengths of the specimens containing HDPE waste as 78%, 99%, and 81% of the splitting tensile strength of conventional concrete for the 10%, 15%, and 20% replacements, respectively. Shamnugapriya and Santhi noted this decrease in strength is due to the weak bond between the HDPE waste and the cement paste. The possible reason for the 15% replacement having a higher splitting tensile strength than the 10% replacement but results for all three tests indicated similar behavior to conventional concrete.

Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017)

Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017) examined the splitting tensile strength of concrete after replacing coarse aggregate with PET plastic aggregate in percentages of 10%, 15%, and 20%. Tamang et al. used a w/c ratio of 0.45 and the splitting

tensile test was conducted in accordance with IS 5816 using 150 mm x 75 mm (5.9 inch x 3 inch) cylinders. Refer to Table 3.5 for concrete mix design information. The results indicated the 28-day splitting tensile strength containing PET plastic replacement showed a 35% decrease for the 10% replacement, 30% decrease for the 15% replacement, and 38% decrease for the 20% replacement. Tamang et al. did not discuss the reason why the splitting tensile strength decreased but only that the 15% replacement is the optimum replacement percentage to achieve the maximum splitting tensile strength.

Costello (2021)

Costello (2021) replaced the coarse aggregate in concrete with Plazrok in percentages of 15%, 30%, and 45% and a w/c ratio of 0.45. Refer to Table 3.6 for concrete mix design information. The splitting tensile test was conducted with cylindrical samples in accordance with ASTM C496. Costello stated that the percent decrease in the 28-day splitting tensile strength is inconsistent for each mix design. The results showed the 15% replacement decreased the least with only a 3.2% decrease while the 30% replacement had a 4.2% decrease and the 45% replacement had a 21.9% decrease in strength. Costello stated the lack of consistent trends could be due to the fact concrete is brittle in tension and the method in which the splitting tensile tests are performed. The machine used for this test was a manually operated hydraulic press that does not always deliver consistent loadings causing the cylinders to split very suddenly. Costello concluded it is possible the breaks occurred at specific points where the aggregate was not fully bonded with the cement paste or at points where it was not distributed as well. Costello recommended that more examinations/testing should be done.

3.2.4 Comparison of Splitting Tensile Strength Test Results

From these varying results on the splitting tensile strength of concrete after partial replacement of coarse aggregate with concrete, several tables and graphs were made to compare the results and look for any common trends. The results in the tables are ordered from lowest to highest w/c ratio. The average decrease for a 10% replacement was 10.7%, the average decrease for a 15% replacement was 13.9%, and the average decrease for a 20% replacement was 26.7%. using these averages, Eq 3.6 was created as an estimate to determine the splitting tensile strength of concrete after plastic replacement. Because this equation had to satisfy all three percentages of replacement, it is not a perfect equation but rather a close estimate.

$$f_{t \text{ replacement}} = \frac{100 - (r + 2)}{100} f_t \quad \text{Eq. 3.6}$$

where:

$f_{t \text{ replacement}}$ = resulting tensile strength;

f_t = tensile strength of control mix;

r = percent of plastic replacement.

Table 3.13 shows the results of the splitting tensile strength with 10% partial replacement. The solid lines indicate the control mixes with no replacement and the dashed lines indicate the splitting tensile strength after the replacement. As indicated, the 28-day splitting tensile strength from all the experiments showed a decrease from their corresponding conventional concrete. Manjunath (2016), with a w/c ratio of 0.5, had the best results with the resulting the 28-day splitting tensile strength only decreasing by 2%. In contrast, Tamang et al. (2017) had the lowest resulting 28-day splitting tensile strength that was 65% of the conventional concrete even though an average and favorable w/c ratio of 0.45 was used. Tamang et al.'s

(2017) results were removed when finding the average decrease for a 10% because of this high decrease compared to other tests. However, Taman et al. (2017) was the only one here who used PET plastic so it might be why their results deferred. The other authors, Shamnugapriya and Santhi (2017), Akram et al. (2015), and Prasanna and Rao (2014) had very comparable results since both had a 10% replacement and a small decrease in strength should occur. Figure 3.9 summarizes the results of Table 3.13 by graphing the resulting splitting tensile strength versus curing days. Figure 3.9 indicates the results vary with Tamang et al. (2017), Akram et al. (2015), and Shamnugapriya and Santhi (2017) being close together at the bottom with lower strengths. Manjunath (2016) had higher splitting tensile strengths. However, Prasanna and Rao (2014) would be considered an outlier here due to it being at the very top and not close in range to all the other results. This might be due to the fact that a w/c ratio was not provided, and it could have been low compared to the others causing the splitting tensile strength to be high.

Table 3.13 Splitting Tensile Strength with 10% Replacement.

Source	Days	w/c	Replacement	ft (Mpa)	ft (psi)	Control ft (MPa)	Control ft (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	10% HDPE	1.42	206.0	1.3	181.3	-13.6*
	14	0.42	10% HDPE	1.95	282.8	2.9	413.4	31.6
	28	0.42	10% HDPE	2.5	362.6	3.2	464.1	21.9
Tamang et al. (2017)	7	0.45	10% PET	1.13	163.9	1.7	249.5	34.3
	14	0.45	10% PET	1.68	243.7	2.3	332.1	26.6
	28	0.45	10% PET	2.07	300.2	3.2	464.1	35.3
Akram et al. (2015)	7	0.5	10% E-Plastic	1.67	242.2	2.3	326.3	25.8
	14	0.5	10% E-Plastic	2.06	298.8	2.4	345.2	13.4
	28	0.5	10% E-Plastic	2.2	319.1	2.5	358.2	10.9
Manjunath (2016)	7	0.55	10% E-Plastic	4.3	623.7	4.3	623.7	0.0
	14	0.55	10% E-Plastic	4.4	638.2	4.7	675.9	5.6
	28	0.55	10% E-Plastic	4.8	696.2	4.9	710.7	2.0
Prasanna and Rao (2014)	7	-	10% E-Plastic	6.06	878.9	6.6	957.2	8.2
	14	-	10% E-Plastic	6.15	892.0	7	1018.2	12.4
	28	-	10% E-Plastic	6.81	987.7	7.4	1074.7	8.1
*A negative sign indicates an increase in strength.								

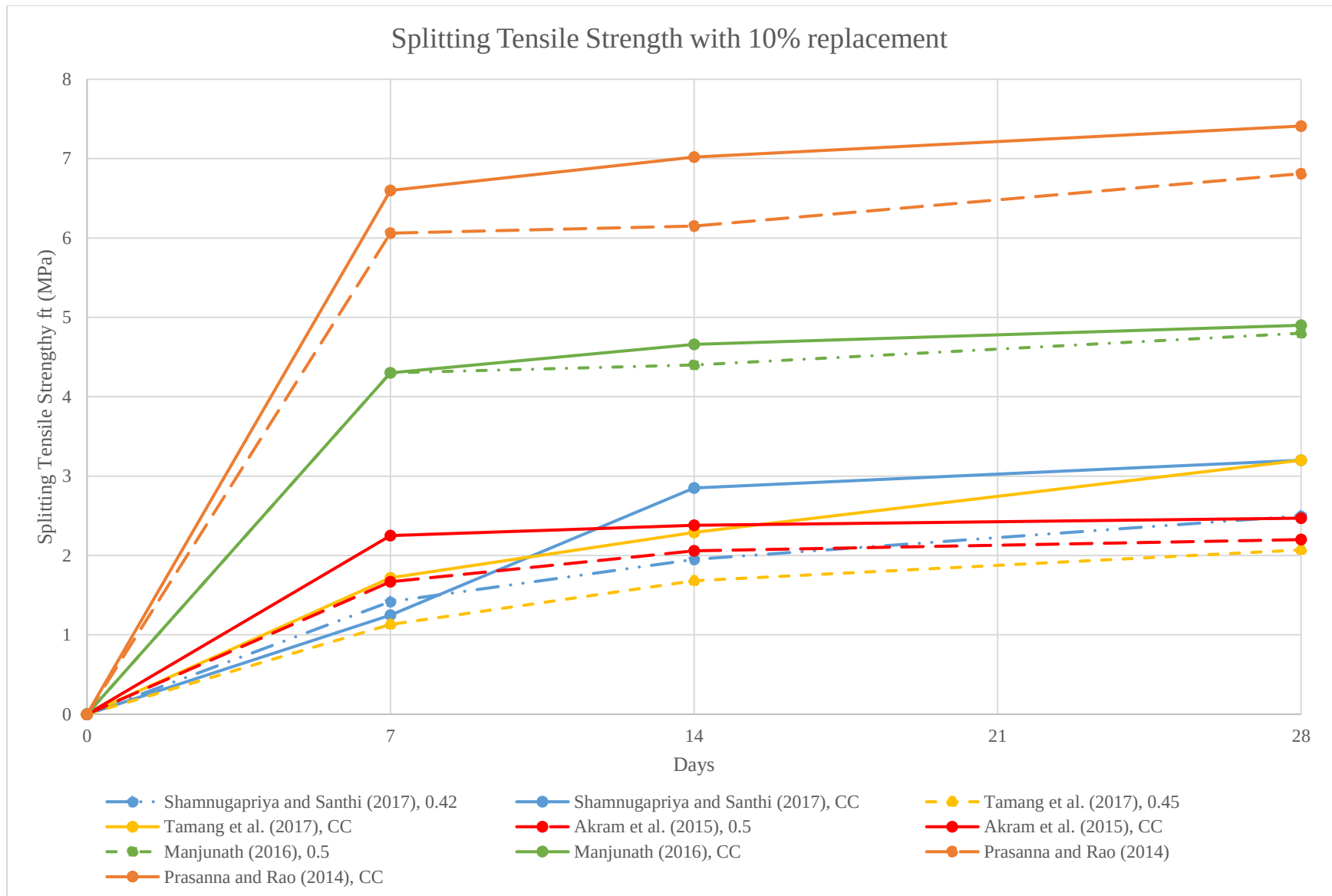


Figure 3.9 Splitting Tensile Strength with 10% Replacement.

Table 3.14 shows resulting splitting tensile strength with 15% partial plastic replacement of coarse aggregate. The results indicate the 28-day splitting tensile strength decreases as plastic is increase to replacement of natural, coarse aggregate and all experiments used the average and recommended w/c ratios of 0.42-0.5. Costello (2021) and Shamnugapriya and Santhi (2017) showed the best results with the resulting 28-day splitting tensile strength only decreasing by 3% and 1%, respectively. Tamang et al. (2017) had the highest decrease in the 28-day splitting tensile strength with being 30%; however, this result could still be comparable to their control group as the decrease was not that big. Akram et al. (2015) and Prasanna and Rao (2014) have comparable results in their 28-day splitting tensile strength to their corresponding conventional concrete with a slight decrease of up to 20%, both using E-Plastic replacements. The results discussed from Table 3.14 are shown in Figure 3.10 with the resulting splitting tensile strength graphed versus curing days. Even though the results varied, they were very close in range with Prasanna and Rao's (2014) results being an outlier due to the high strengths achieved which could be due to the unknown w/c ratio possibly being low.

Table 3.14 Splitting Tensile Strength with 15% Replacement.

Source	Days	w/c	Replacement	ft (Mpa)	ft (psi)	Control ft (MPa)	Control ft (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	15% HDPE	1.95	282.8	1.3	181.3	-56.0*
	14	0.42	15% HDPE	2.52	365.495	2.9	413.4	11.6
	28	0.42	15% HDPE	3.17	459.76951	3.2	464.1	0.9
Tamang et al. (2017)	7	0.45	15% PET	1.45	210.3	1.7	249.5	15.7
	14	0.45	15% PET	1.98	287.2	2.3	332.1	13.5
	28	0.45	15% PET	2.25	326.33483	3.2	464.1	29.7
Costello (2021)	7	0.45	15% Plazrok	2.3	333.6	2.5	359.7	7.3
	14	0.45	15% Plazrok	2.17	314.7	2.4	343.7	8.4
	28	0.45	15% Plazrok	2.2	319.1	2.3	329.2	3.1
Akram et al. (2015)	7	0.5	15% E-Plastic	1.48	214.7	2.3	326.3	34.2
	14	0.5	15% E-Plastic	1.73	250.9	2.4	345.2	27.3
	28	0.5	15% E-Plastic	2.08	301.7	2.5	358.2	15.8
Prasanna and Rao (2014)	7	-	15% E-Plastic	4.11	596.1	6.6	957.2	37.7
	14	-	15% E-Plastic	4.65	674.4	7.0	1018.2	33.8
	28	-	15% E-Plastic	5.91	857.2	7.4	1074.7	20.2

*A negative sign indicates an increase in strength.

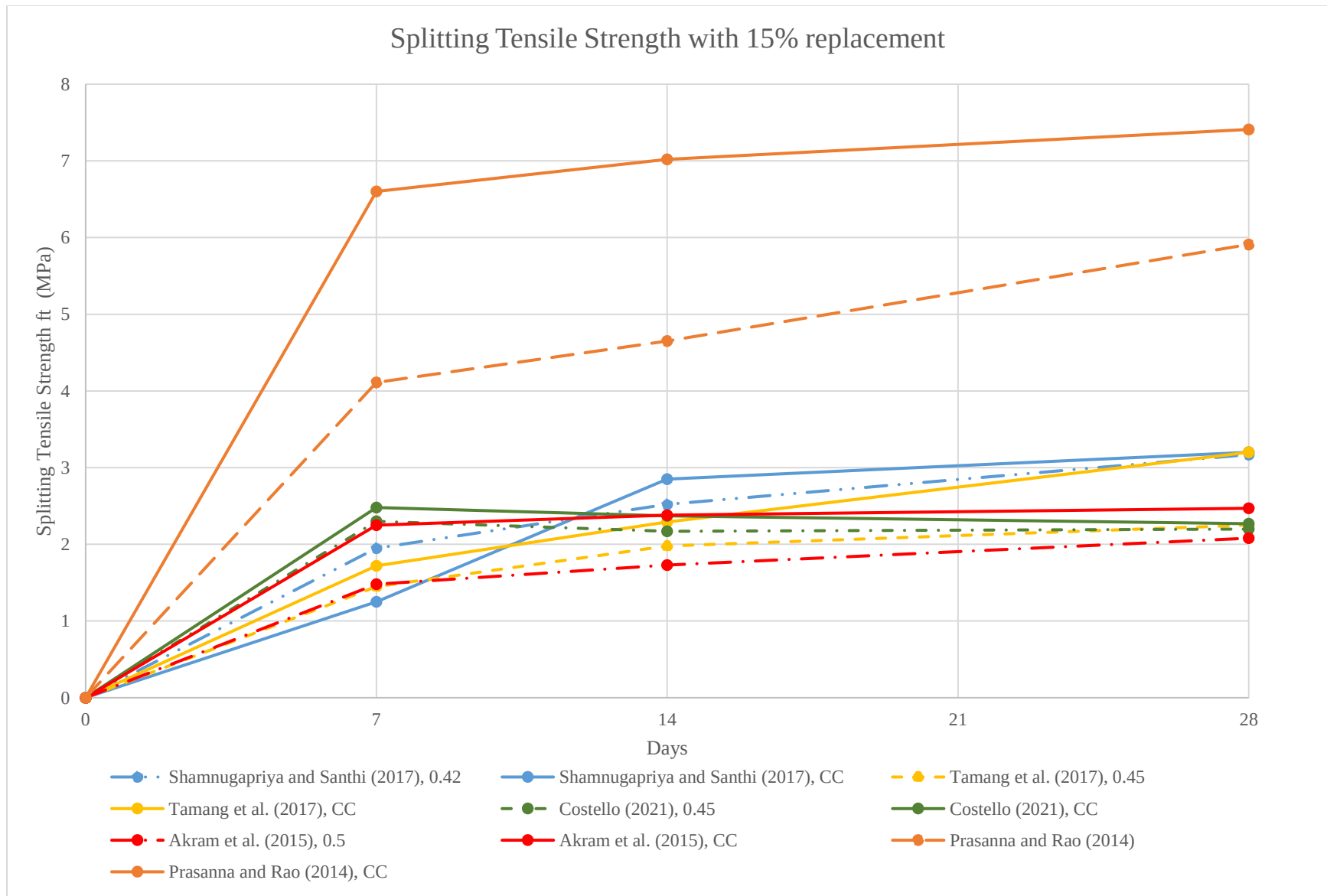


Figure 3.10 Splitting Tensile Strength with 15% Replacement.

The results of the splitting tensile strength with 20% plastic replacement of coarse aggregate are shown in Table 3.15. Surprisingly, Manjunath (2016), using E-Plastics and w/c ratio of 0.5, had an increase of 10% in the 28-day splitting tensile strength with plastic replacement compared to their conventional concrete. In contrast, Tamang et al. (2017) and Prasanna and Rao (2014) had a big decrease in the resulting 28-day splitting tensile strength with a decrease of 38% and 60%, respectively. Shamnugapriya and Santhi (2017) had a comparable resulting 28-day splitting tensile strength to their control group that showed a decrease of only 20%. The results vary in Figure 3.11 where the resulting splitting tensile strength is graphed versus curing days.

Table 3.15 Splitting Tensile Strength with 20% Replacement.

Source	Days	w/c	Replacement	ft (Mpa)	ft (psi)	Control ft (MPa)	Control ft (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	20% HDPE	1.7	250.9	1.3	181.3	-38.4*
	14	0.42	20% HDPE	2.2	314.7	2.9	413.4	23.9
	28	0.42	20% HDPE	2.6	377.1	3.2	464.1	18.8
Tamang et al. (2017)	7	0.45	20% PET	1.7	242.2	1.7	249.5	2.9
	14	0.45	20% PET	1.7	240.8	2.3	332.1	27.5
	28	0.45	20% PET	2.0	287.2	3.2	464.1	38.1
Manjunath (2016)	7	0.55	20% E-Plastic	3.2	456.9	4.3	623.7	26.7
	14	0.55	20% E-Plastic	5.0	725.2	4.7	675.9	-7.3*
	28	0.55	20% E-Plastic	5.4	783.2	4.9	710.7	-10.2*
Prasanna and Rao (2014)	7	-	20% E-Plastic	2.5	356.8	6.6	957.2	62.7
	14	-	20% E-Plastic	2.7	393.1	7.0	1018.2	61.4
	28	-	20% E-Plastic	2.9	426.4	7.4	1074.7	60.3
*A negative sign indicates an increase in strength.								

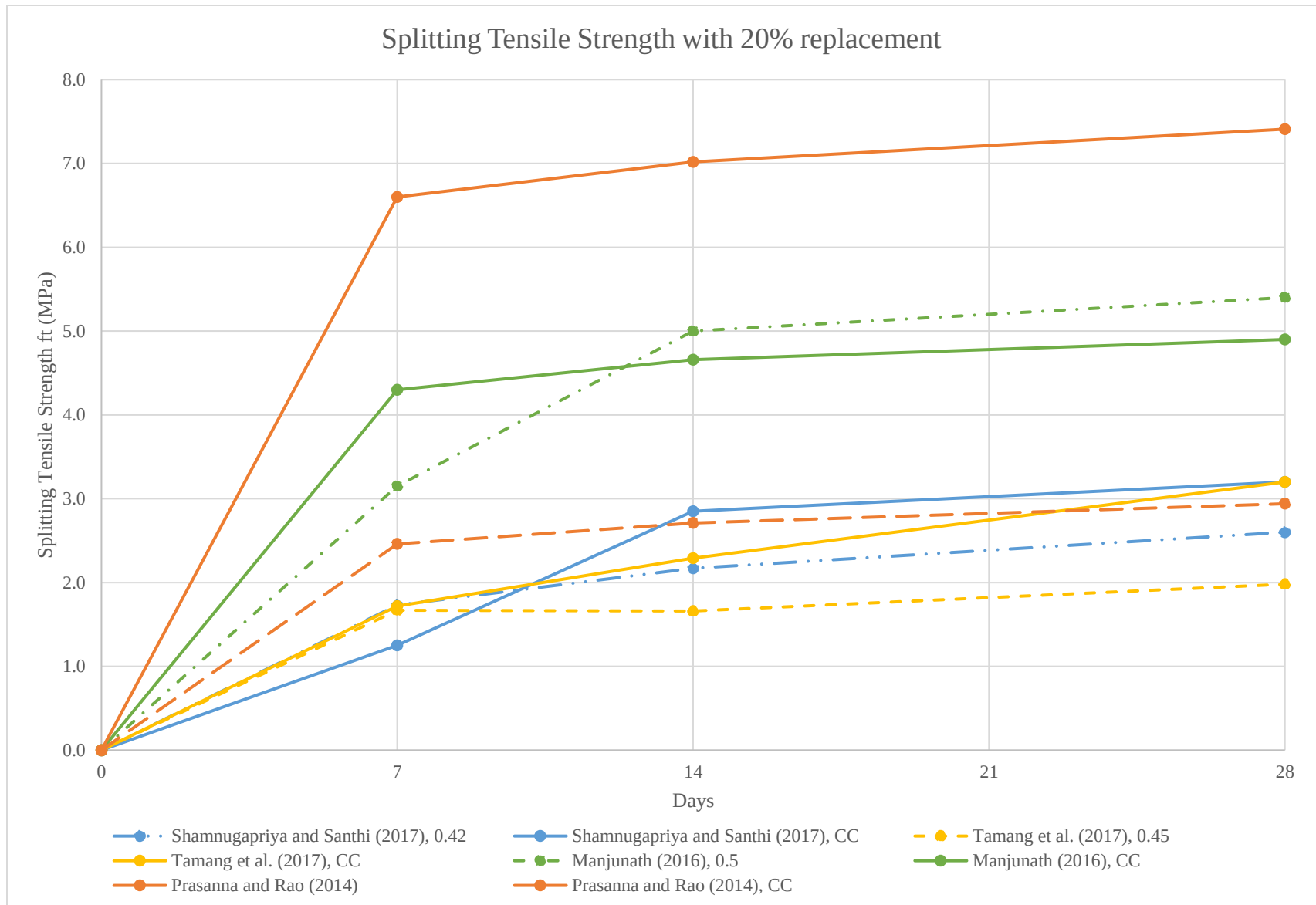


Figure 3.11 Splitting Tensile Strength with 20% Replacement.

3.3 Modulus of Rupture

3.3.1 Importance of Modulus of Rupture

The modulus of rupture is an indication of the flexural strength of concrete and is a measure of the tensile strength of concrete beams or slabs. The flexural strength identifies the amount of stress and force the concrete can withstand before it experiences any bending failures. By definition, the flexural strength of a concrete specimen is the ultimate tensile stress due to bending taken by the concrete of tension zone of specimen (Singh, 2022). The flexural strength of concrete is approximately 10% to 15% of the compressive strength of concrete depending on the type, volume, and size of coarse aggregate used (Deloney, 2023). The modulus of rupture is used for estimating both the resistance and durability of materials and it helps determine the design and quality of structures for constructions. The modulus of rupture is calculated using Eq. 3.7 from the ACI code (ACI 318-19).

$$f_r = 7.5\lambda\sqrt{f'_c} \quad \text{Eq. 3.7}$$

where:

f_r = Modulus of rupture;

λ = value obtained in accordance with 19.2.4 (ACI 318-19);

f'_c = 28-day compressive strength.

3.3.2 Test Methods to Determine Modulus of Rupture

Similar to the other test methods, two methods are commonly used to determine the flexural strength of concrete. These utilize the American Society of the International Association for Testing and Materials (ASTM) standards. ASTM C496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens offers a method to determine the modulus of

rupture by loading at the center point. ASTM C78 Test Methods for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) offers a method to determine the modulus of rupture by loading at third points. However, the modulus of rupture determined by the loading of the third point is less than the modulus of rupture determined by the loading of the center point, sometimes up to 15% (Deloney, 2023). ASTM C496 is discussed above in section 3.2.2. ASTM C78 requires the specimen to be turned on its side and centered on the support blocks in relation to the applied force. The loading blocks are put on the specimen at the third points and a force is applied between 3% to 6% of the estimated ultimate force. A leaf-type feeler gauge is used to determine if a gap between the specimen and the loading support or support block exists. If so, leather shims are used on the specimen contact surface to eliminate any gap in excess of 0.1 mm (0.004 in.) in width. The load is then applied continuously and without shock. The load should be applied at a rate that constantly increases the maximum stress on the tension face between 0.9 MPa/min and 1.2 MPa/min (125 psi/min and 175 psi/min) until rupture occurs. Eq. 3.8 is used to determine the modulus of rupture (ASTM C78).

$$R = \frac{PL}{bd^2} \quad \text{Eq. 3.8}$$

where:

R = modulus of rupture, MPa (psi);

P = maximum applied load, N (lbf);

L = span length, mm (in);

b = average width of specimen at the fracture, mm (in);

d = average depth of specimen at fracture, mm (in).

Another common testing method used to determine the flexural strength of concrete is the Indian Standard *IS 156-1959 Methods of Tests for Strength of Concrete* section 7 using beam specimens. The standard size of the specimen is to be 150 x 150 x 700 mm (5.9 x 5.9 x 27.6 inch). The testing machine is to be provided with two steel rollers that support the specimen and they should be mounted so that the distance between them is 40 to 60 cm (15.7 to 23.6 inch). The axis of the specimen should be carefully aligned with the axis of the loading device. The load is then applied through two similar rollers mounted at the third points of the supporting span and the load should be divided equally between the two loading rollers and they should be positioned in a manner that the load is applied axially. The load should be applied without shock while increasing continuously until the specimen fails. The maximum load applied should be recorded and any fractures or unusual features in the type of failure should be noted (IS 156-1959).

3.3.3 Modulus of Rupture of Concrete After Plastic Replacement

In contrast to the research and studies done on the compressive strength of concrete containing plastic, coarse aggregate replacement, very few studies on the modulus of rupture (flexural strength) of concrete with recycled or waste plastic partial replacement of natural, coarse aggregate have been documented. In the research examined for this thesis, results varied and little discussion was provided as to why some specimens had an increase in flexural strength while others had a decrease in the flexural strength. Four studies have been examined and discussed here.

Manjunath (2016)

Manjunath (2016) replaced the coarse aggregate in concrete with E-plastic waste in percentages of 10%, 20%, and 30%. The concrete had a w/c ratio of 0.5 and the specimens were tested in 150 x 150 x 700 mm (5.9 x 5.9 x 27.6 inch) beams for flexural strength per IS 516. 101%, 99%, and 57% of the 28-day flexural strength for the conventional concrete was achieved for the specimens with 10%, 20%, and 30% replacement, respectively. Manjunath concluded the flexural strength of concrete containing plastic waste decreases for specimens with replacement more than 20% but is acceptable for less replacements.

Shamnugapriya and Santhi (2017)

Shamnugapriya and Santhi (2017) conducted tests on the flexural strength of concrete by replacing coarse aggregate with 10%, 15%, and 20% HDPE plastics with a 0.42 w/c ratio. Refer to Table 3.4 for concrete mix design information. The modulus of rupture test was conducted in accordance to IS 516 using 500 mm x 100 mm x 100 mm (19.7 inch x 3.9 inch x 3.9 inch) prismatic specimens. The specimens were subjected to four-point loading using a universal testing machine. The 28-day flexural strength of the specimens with 10% replacement increased by 10% compared to that only containing natural coarse aggregate and the 15% replacement increased by 65%. However, the 20% replacement decreased by 16%. Shamnugapriya and Santhi concluded that the specimens containing HDPE show superior performance than conventional cement concrete mix. No discussion on the high increase of the flexural strength at the 15% replacement was provided.

Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017)

Tamang, Wanmego, Darjay, Phuntsho, Namgyal, and Wangchun (2017) used PET plastic to replace coarse aggregate in concrete in percentages of 10%, 15%, and 20%. Refer to Table 3.5 for concrete mix design information. Tamang et al. used a w/c ratio of 0.45 and the flexural strength test was conducted in accordance with IS 516 using 100 x 100 x 500 mm (3.9 x 3.9 x 19.7 inch) beams. The 28-day flexural strength of the concrete containing 10%, 15%, and 20% PET coarse aggregate was 87%, 97%, and 92% of the 28-day flexural strength of the conventional concrete, respectively. Tamang et al. briefly discussed the results stating they were desirable and comparable since little decrease in the flexural strength occurred.

3.3.4 Comparison of Modulus of Rupture Test Results

Since few experiments were conducted on the modulus of rupture of concrete with partial plastic replacement only 10% and 20% replacement results were gathered. The results in the tables are ordered from lowest to highest w/c ratio. The average decrease for a 10% replacement was 0.5%, and the average decrease for a 20% replacement was 8.3%. Using these averages, Eq 3.9 was created as an estimate to determine the modulus of rupture of concrete after plastic replacement. Because this equation had to satisfy the two percentages of replacement, it is not a perfect equation but rather a close estimate.

$$f_{s \text{ replacement}} = \frac{100 - (r + 4)}{100} f_s \quad \text{Eq. 3.9}$$

where:

$f_{s \text{ replacement}}$ = resulting modulus of rupture;

f_s = modulus of rupture of control mix;

r = percent of plastic replacement.

Table 3.16 shows results of the modulus of rupture after a 10% partial replacement of coarse aggregate with plastic waste. The solid lines indicate the control mixes with no replacement and the dashed lines indicate the modulus of rupture after the replacement. These results indicate that a 10% replacement may not have that much of an effect on the flexural strength of concrete. Tamang et al. (2017) was the only one who showed a decrease in the 28-day flexural strength, the result being 87% than that of conventional concrete. This might be due to Tamang et al. (2017) being the only one using PET plastic replacements. Shamnugapriya and Santhi (2017) and Manjunath (2016) showed either a slight increase or no difference in the resulting 28-day flexural strength. Their resulting 28-day flexural strength for their 10% replacement increased by 10%, did not change at all, and increased by 1%, respectively. The results from Table 3.16 are graphed in Figure 3.12 with the resulting flexural strength versus curing days. Although the strength varied in the days leading up to 28 curing days, the 28-day flexural strength was close in range for all the experiments with Tamang et al. (2017) being slightly lower than the rest.

Table 3.16 Flexural Strength with 10% Replacement.

Source	Days	w/c	Replacement	FS (MPa)	FS (psi)	Control FS (MPa)	Control FS (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	10% HDPE	3.2	464.1	2.5	362.6	-28.0*
	14	0.42	10% HDPE	4.04	586.0	3.1	449.6	-30.3*
	28	0.42	10% HDPE	4.25	616.4	3.9	559.8	-10.1*
Tamang et al. (2017)	7	0.45	10% PET	2.07	300.2	2.7	396.0	24.2
	14	0.45	10% PET	2.56	371.3	2.7	397.4	6.6
	28	0.45	10% PET	3.51	509.1	4.0	583.1	12.7
Manjunath (2016)	7	0.5	10% E-Plastic	1.2	174	1.5	217.6	20.0
	14	0.5	10% E-Plastic	2.9	420.6	3.0	435.1	3.3
	28	0.5	10% E-Plastic	4.4	638.2	4.4	630.9	-1.1*
*A negative sign indicates an increase in strength.								

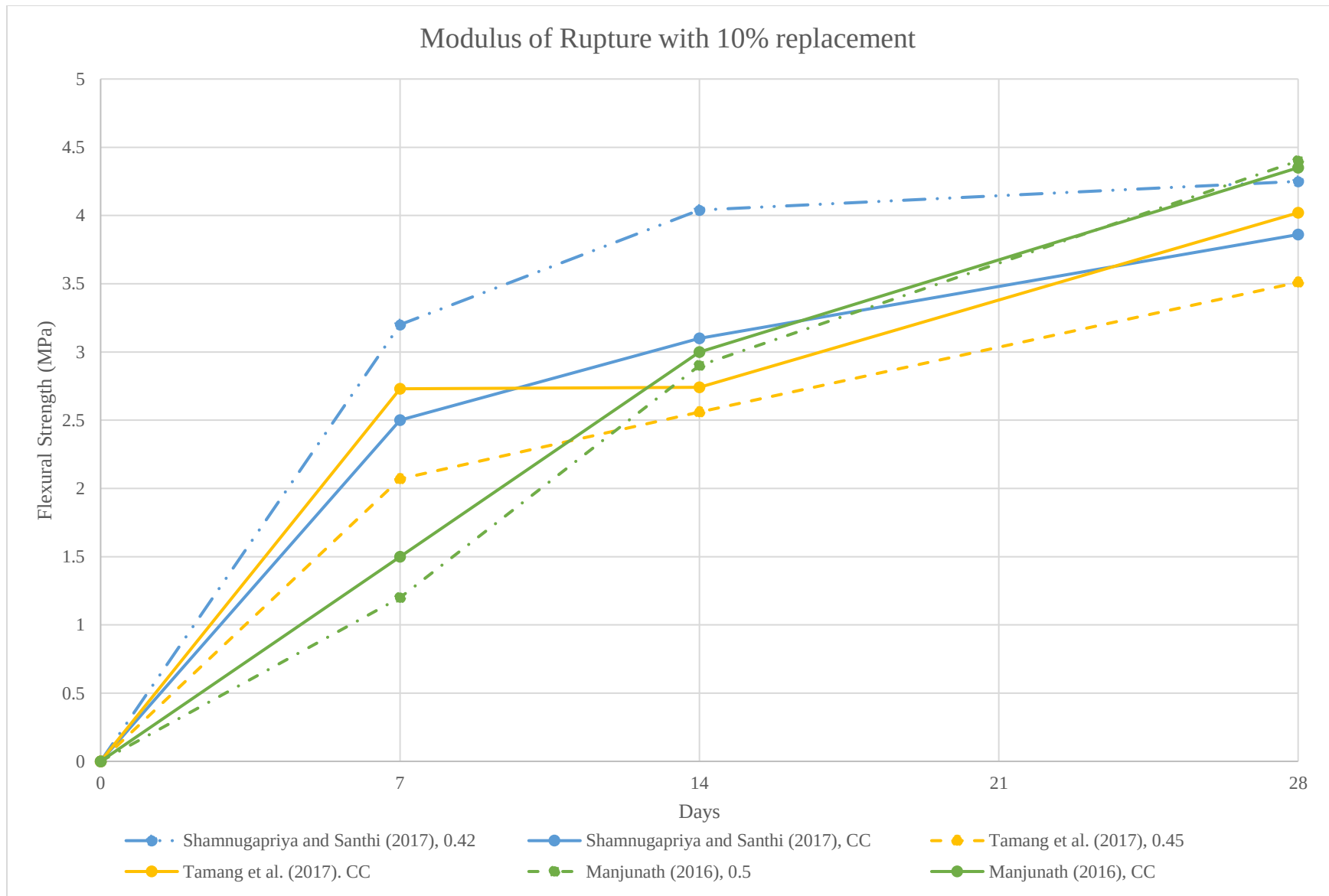


Figure 3.12 Flexural Strength with 10% Replacement.

The last set of results gathered are the modulus of rupture results after a 20% partial plastic replacement. Similar to the 10% replacement, it is shown in Table 3.17 that a 20% replacement does not have a great effect on the modulus of rupture of concrete. The tests were all comparable to their respective control mixes even after a decrease in strength occurred. Shamnugapriya and Santhi (2017) showed a decrease of 16%, Tamang et al. (2017) showed a decrease of 8%, and Manjunath (2016) showed a decrease of only 1%. The results from Table 3.17 are shown in Figure 3.13 where the resulting flexural strength is graphed versus curing days. As shown, Manjunath (2016) produced a linear result which is not that common to have as the specimens cure. The results varied but were not that very far off in range with no outliers present.

Table 3.17 Flexural Strength with 20% Replacement.

Source	Days	w/c	Replacement	FS (MPa)	FS (psi)	Control FS (MPa)	Control FS (psi)	% Decrease
Shamnugapriya and Santhi (2017)	7	0.42	20% HDPE	2.3	333.6	2.5	362.6	8.0
	14	0.42	20% HDPE	3.15	456.9	3.1	449.6	-1.6*
	28	0.42	20% HDPE	3.25	471.4	3.9	558.4	15.6
Tamang et al. (2017)	7	0.45	20% PET	2.6	377.1	2.7	396.0	4.8
	14	0.45	20% PET	2.66	385.8	2.7	397.4	2.9
	28	0.45	20% PET	3.69	535.2	4.0	583.1	8.2
Manjunath (2016)	7	0.5	20% E-Plastic	1.0	145.0	1.5	217.6	33.3
	14	0.5	20% E-Plastic	2.0	290.1	3.0	435.1	33.3
	28	0.5	20% E-Plastic	4.3	623.7	4.4	630.9	1.1
*A negative sign indicates an increase in strength.								

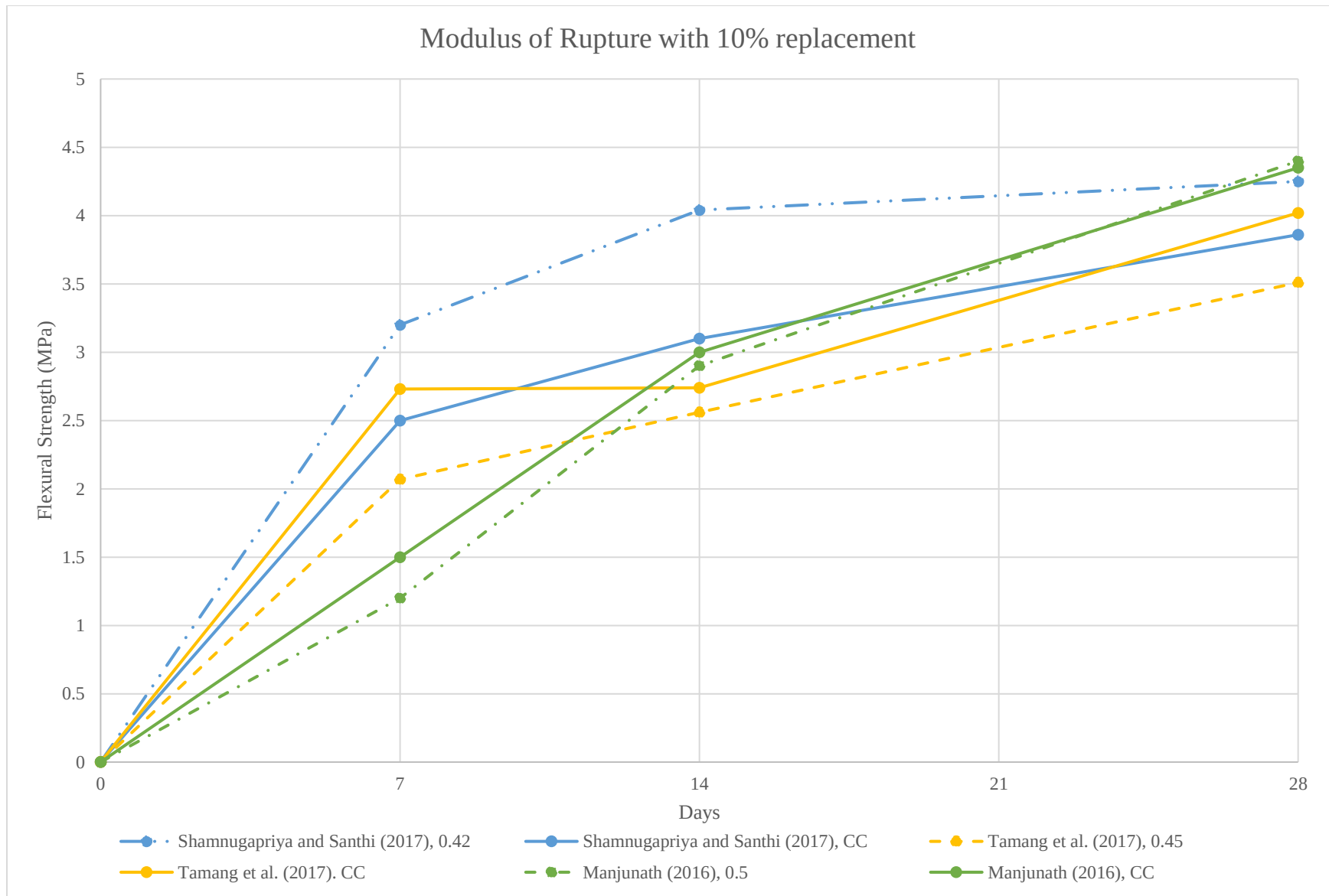


Figure 3.13 Flexural Strength with 20% Replacement

3.4 Modulus of Elasticity

3.4.1 Importance of Modulus of Elasticity

The modulus of elasticity of concrete is defined as the ratio of the applied stress to the corresponding strain (CivilWeb, 2020). It also measures the stiffness of the concrete or how much the concrete will deflect under load, including deflection. The stress-strain curve of concrete starts as linear then becomes nonlinear which indicates that concrete is only an elastic material up to an extent, 0.45 of the compressive strength (Subramanian, 2021). This means that if the concrete is loaded to any value of stress within the elastic part of the curve, it will return to its original shape. To simplify this, the modulus of elasticity of concrete is the slope of its stress-strain plot within the elastic range. The modulus of elasticity of concrete is required for the estimation of the deformation of buildings and members. The modulus of elasticity is dependent on the concrete's compressive strength and affected by the same factors. Some of those factors include air content, w/c ratio, quality of the cement paste, and the properties of the aggregates (CivilWeb, 2020). The modulus of elasticity of concrete can vary between 14 and 41 GPa (2 and 6 x 10⁶ psi). The modulus of elasticity is calculated using Eq. 3.10 and Eq. 3.11 from the ACI code (ACI 318-19).

For values of w_c between 90 and 160 lb/ft³:

$$E_c = w_c^{1.5} 33 \sqrt{f'_c} \quad (\text{in psi}) \quad \text{Eq. 3.10}$$

For normal weight concrete:

$$E_c = 57000 \sqrt{f'_c} \quad (\text{in psi}) \quad \text{Eq. 3.11}$$

where:

E_c = Modulus of elasticity;

w_c = weight of concrete;

f'_c = 28-day compressive strength.

3.4.2 Test Methods to Determine Modulus of Elasticity

A common way to determine the modulus of elasticity of concrete is by using ASTM C469 *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. Cylindrical specimens are prepared by being moist cured. After they are removed from the water, they are kept moist by a wet cloth covering during the interval between removal and test. First, a companion specimen is tested for compression using ASTM C39 and the ultimate load is recorded. The testing machine used for this procedure is a compressometer that is attached to the specimen and it consists of two yokes, one of which is rigidly attached to the specimen and the other is attached at two diametrically opposite points so that it is free to rotate. The specimen is placed on the lower plate of the testing machine with the strain-measuring equipment attached. The specimen should be loaded at least three times without recording data from the first loading. During the first loading, the performance of the gauges is observed, and attachments are corrected prior to the second loading. The load is then applied again continuously and without shock until it reaches 40 % of the average ultimate load of the

companion specimens. This is the maximum load that should be used in the following equation Eq. 3.12 provided in the standard to calculate the modulus of elasticity (ASTM C469).

$$E = \frac{(S_2 - S_1)}{(\epsilon_2 - 0.00005)}$$

where:

E = chord modulus of elasticity, MPa (psi);

S₂ = stress corresponding to 40% of ultimate load;

S₁ = stress corresponding to longitudinal strain, ϵ_1 , of 50 millionth, MPa (psi);

ϵ_2 = longitudinal strain produced by stress S₂.

3.4.3 Modulus of Elasticity of Concrete After Plastic Replacement

Very few studies on the modulus of elasticity of concrete with recycled or waste plastic partial replacement of coarse aggregate have been documented. In the research examined for this thesis, results varied, and little discussion was provided as to why some specimens had an increase in the modulus of elasticity while others had a decrease in the modulus of elasticity. Three studies have been examined and discussed here, listed from oldest to newest.

Ghaly and Gill (2004)

Ghaly and Gill prepared concrete cube specimens containing 5%, 10%, and 15% partial replacement of coarse aggregate with recycled plastic. For more information on this research refer to section 3.1.3. The stress-strain relationship of the concrete specimens was used to determine the modulus of elasticity for each w/c (0.42, 0.54, 0.69) mix. Ghaly and Gill found that as the percentage of plastic waste replacement increases, the modulus of elasticity decreases

for the 0.54 and 0.69 w/c ratios. However, for the 0.42 w/c ratio, the modulus of elasticity increased by 16%, 8%, and 8% for the 5%, 10%, and 15% replacement, respectively. Ghaly and Gill did not discuss this increase for the 0.42 w/c ratio, just the decrease in the other two w/c ratios by saying they portray a general trend of decreasing as the percentage of replacement increases. Ghaly and Gill concluded that for a given w/c ratio and the greater the plastic content in the mix, the lower the modulus of elasticity.

Saxena, Gupta, Sharma, Chaudhary, and Jain (2016)

Saxena et al. conducted tests to measure the modulus of elasticity of concrete containing partial replacement of coarse aggregate with PET plastic in percentages of 5%, 10%, 15%, and 20%. Concrete cylindrical specimens were prepared and tested as per ASTM C469. A constant w/c ratio of 0.45 was used for all test specimens. The modulus of elasticity was observed after 28 days of curing and showed a constant decrease as the plastic replacement increased. Saxena et al. noted that the modulus of elasticity decreased by 4% for the 5% replacement, 22% for the 10% replacement, 46% for the 15% replacement, and 50% for the 20% replacement. Saxena et al. concluded the modulus of elasticity gradually decreased due to PET being less resistant than natural aggregates and deforming less when an equivalent stress is applied.

Islam and Shahjalal (2021)

Islam and Shahjalal prepared a total of 96 cylindrical concrete specimens with 0.45 and 0.55 w/c ratios to collect the stress-strain data to calculate the elastic modulus as per ASTM C469. Each set of w/c ratio had partial plastic replacement, using PP plastic, of coarse aggregate in percentages of 10%, 20%, and 30%. Islam and Shahjalal stated the modulus of elasticity

decreased as the replacement increased and was lower for the 0.55 w/c than the 0.45 w/c ratio. For the 0.45 w/c ratio, the modulus of elasticity decreased by 4% for the 10% replacement, 11% for the 20% replacement, and 27% for the 30% replacement. For the 0.55 w/c ratio, the modulus of elasticity decreased by 14% for the 10% replacement, 21% for the 20% replacement, and 37% for the 30% replacement. Islam and Shahjalal concluded that the decrease in modulus of elasticity possibly occurred to PP being a soft material and deforming easily while exhibiting a lower stiffness.

3.4.4 Comparison of Modulus of Elasticity Test Results

The average decrease for a 5% replacement was 1%, the average decrease for a 10% replacement was 10%, the average decrease for a 15% replacement was 22%, the average decrease for a 20% replacement was 27%, the average decrease for a 30% replacement was 32%. Using these averages, Eq 3.11 was created as an estimate to determine the modulus of elasticity of concrete after plastic replacement. Because this equation had to satisfy all three percentages of replacement, it is not a perfect equation but rather a close estimate.

$$MoE_{replacement} = \frac{100 - (r + 3)}{100} MoE \quad \text{Eq. 3.11}$$

where:

$MoE_{replacement}$ = resulting modulus of elasticity;

MoE = modulus of elasticity of control mix;

r = percent of plastic replacement.

Table 3.18 provides the summarized modulus of elasticity results of Ghaly and Gil, Saxena et. al., and Islam and Shahjalal ordered from lowest w/c ratio to highest. The results are graphed and shown in Figure 3.14. As previously discussed, the modulus of elasticity of concrete containing only natural aggregated varies between 14 and 41 GPa (2 and 6 x 10⁶ psi). Therefore, Ghaly and Gill had overall lower modulus of elasticity results than what is usually desired for concrete which is why their results differ than Saxena et. al. and Islam and Shahjalal. As shown in Figure 3.14, Saxena et. al. was the only one who had a sudden decrease after the 5% replacement, this could be due to Saxena et. al. using a different type of plastic than Ghaly and Gill, who did not specify a type of plastic, and Islam and Shahjalal, who used PP plastic. Both w/c ratios examined for Islam and Shahjalal showed a gradual decrease in the modulus of elasticity as the percentage of plastic replacement increased.

Table 3.18 Modulus of Elasticity with Various Replacements

Source	w/c	Replacement	MoE (GPa)	MoE (psi)	% Decrease
Ghaly and Gill (2004)	0.42	0%	4.9	710685	0
	0.42	5%	5.7	826715	-16*
	0.42	10%	5.3	768700	-8*
	0.42	15%	5.3	768700	-8*
Saxena et. al. (2016)	0.45	0% PET	26	3770981	0
	0.45	5% PET	24.9	3611439	4
	0.45	10% PET	20.4	2958770	22
	0.45	15% PET	14.1	2045032	46
	0.46	20% PET	13	1885490	50
Islam and Shahjala (2021)	0.45	0% PP	28	4061056	0
	0.45	10% PP	26.8	3887011	4
	0.45	20% PP	25	3625943	11
	0.45	30% PP	20.4	2958770	27
Ghaly and Gill (2004)	0.54	0%	6.4	928241	0
	0.54	5%	5.9	855723	8
	0.54	10%	5.7	826715	11
	0.54	15%	5.5	797708	14
Islam and Shahjala (2021)	0.55	0% PP	25.6	3712966	0
	0.55	10% PP	22	3190830	14
	0.55	20% PP	20.2	2929762	21
	0.55	30% PP	16	2320604	38
Ghaly and Gill (2004)	0.69	0%	5.9	855723	0
	0.69	5%	5.5	797708	7
	0.69	10%	4.7	681677	20
	0.69	15%	3.7	536640	37
*A negative sign indicates an increase.					

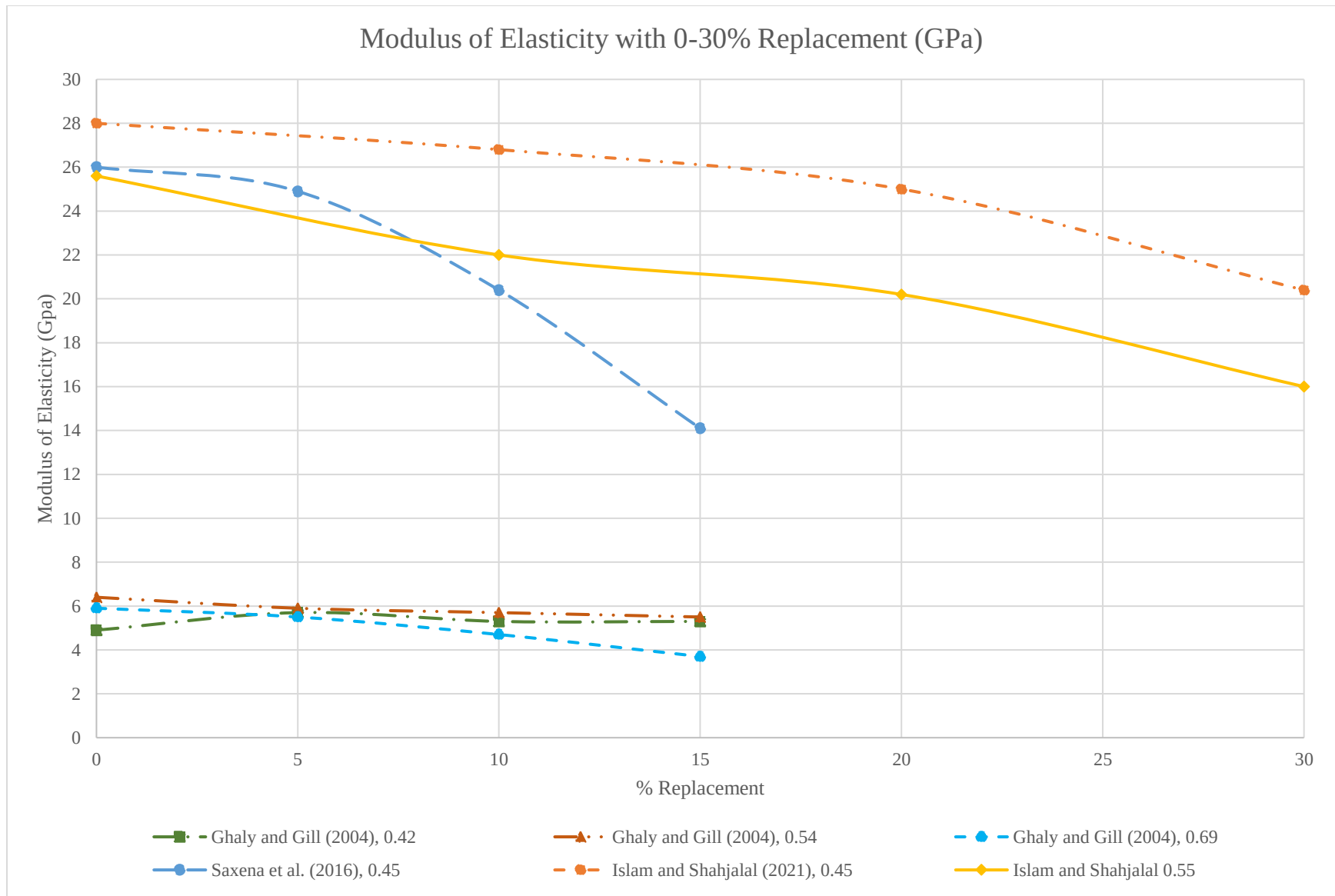


Figure 3.14 Modulus of Elasticity with Various Replacement

Chapter 4 - Conclusion

Efforts have been taken to save nature from losing natural resources and control the increased number of plastic waste without compromising the overall performance of concrete. This was done through the use of plastic waste as a partial replacement of coarse aggregate in the concrete. Many studies have been done to examine how the partial plastic replacement in the concrete mix would affect its engineering properties. It has been shown that up to a certain level, the properties of plastic waste could be suitable to produce new concrete.

Based on the results discussed in this thesis, it was seen that the type of plastic used does not affect the concrete but rather any plastic waste that is used could potentially decrease the strength of concrete. The compressive strength, splitting tensile strength, and the modulus of elasticity of concrete after the plastic replacement decreased as the amount of plastic added increased. However, in some cases the strength increased but it was not discussed in any of the studies why this occurred. All the studies concluded that this decrease in strength could be due to the bond strength between the cement paste and the smooth surface of the plastic and the free water available at the surface of the plastic. In contrast, the modulus of rupture showed the best results with a slight increase or no change in the flexural strength of concrete with partial plastic replacement. There was no discussion provided on this in any of the studies that were examined. A common conception about the concrete mix is the higher the w/c ratios are, the lower the strength of concrete even without any plastic waste replacement. This was true for some of the studies examined but not all because some of the studies with higher w/c ratios had higher strengths than those with lower w/c ratios. Other factors affect the mechanical properties of concrete such as quality and amount of cement; quality, cleanness, and grading of the aggregate; quality and amount of water; presence or lack of admixtures; methods followed in handling and

placing the concrete; age of the concrete when placed in the forms; temperature; curing conditions; and age of the concrete when tested. Additionally, foreign materials may find their way into the concrete, thereby affecting the strength.

Not many common trends from the results examined could be made due to the little information provided on the concrete mix and the discussions on the results. Some studies did not include simple things such as the w/c ratio, the type of plastic used, the testing method used, or the mix design of the concrete. More research on the partial plastic replacement of coarse aggregate in concrete needs to be conducted in order to determine what common trends can be concluded on things such as the type of plastic waste used, the amount of replacement, the w/c ratio, and the concrete mix. Once common trends are found it will be easy to predict how plastic waste can be utilized in concrete and how it will affect the mechanical properties of concrete. This thesis is a good place for upcoming studies interested in furthering the research on this topic because it provides summarized tables, graphs, and discussions on the previous studies done.

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