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Utilization of Artificial Coarse Aggregate from Polyethylene Terephthalate Plastic Waste in Concrete

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Abstract – *Plastic waste production is increasing in tandem with increased plastic consumption. Plastic waste used in construction is one of the most environmentally friendly options available for reducing environmental impact. This research is an experiment on the petrography, the porosity, and the mechanical characteristics of concrete using PET (Polyethylene Terephthalate) plastic aggregates to replace natural aggregates. Artificial aggregate by heating PET plastic waste until it reaches a melting point of about 250 °C to- 260 °C, produces concrete with four percentage levels of artificial aggregate substitution, namely 25%, 50%, 75%, and 100%. The mechanical testing of the sample is done after 28 days. The compressive strength of plastic concrete used as a substitute for artificial aggregate in concrete mixtures has been reduced as a result of this research. The replacement of 25% of PET plastic-made aggregates has significantly increased tensile and flexural strength, and PET petrography has revealed cement-filled pores and cracks. The PET artificial aggregate and the cement matrix have adhered perfectly and have formed an impenetrable bond. The exponential power equation may be used to estimate the connection between porosity and compressive strength in concrete using PET plastic artificial aggregates.*

***Keywords**: Plastic Waste, Polyethylene Terephthalate, Petrography, Porosity, Concrete*

Nomenclature

$f'c$	Concrete Compressive strength [MPa]
A	Area of test section [mm^2]
P	Ultimate load [N]
f_f	Concrete flexural strength [MPa]
f_t	Concrete splitting tensile strength [MPa]
B	Sectional width of test object [mm]
D	Specimen cylinder diameter [mm]
L	Length of test object [mm]
h	Height of test object [mm]
ρ_w	Density of water [g/cm^3]
W_d	Dry mass of sample after immersion [g]
W_w	Wet mass of sample after immersion [g]
V_b	Volume of specimen [cm^3]
n, k	Coefficient, a value of n is between 0.5 and 0.85
m, K	Empirical constants
σ	Materials compressive strength [N/mm^2]
p	Porosity
σ_0	Materials compressive strength at zero Porosity [N/mm^2]
π	A rational number that is an approximation (22/7)
PP	Polypropylene
PET-PAA	PET Plastic Artificial Aggregates
PET	Polyethylene Terephthalate
PAA	Plastic Artificial Aggregates
HDPE	High-Density Polyethylene
PVC	Polyvinyl Chloride
LDPE	Low-Density Polyethylene
PCC	Portland Cement Composite
UTM	Universal Testing Machine
ACI	American Concrete Institute
SCC	Self Compacting Concrete
DOE	Development of Environment
CS	Standard Concrete
C100	100% PET artificial aggregate on concrete
C75	75% PET artificial aggregate on concrete
C50	50% PET artificial aggregate on concrete
C25	25% PET artificial aggregate on concrete
H_2O_2	Hydrogen peroxide
$Ca(ClO)_2$	Calcium hypochlorite
SSD	Saturated Surface Dry
ASTM	American Society for Testing and Materials
SiO_2	Silica
H_2O_2	Hydrogen peroxide
$CaCO_3$	Calcium carbonate
CSH	Calcium Silicate Hidrate (Tobermorite)
CH	Calcium Hidrate (Portlandite)

I. Introduction

Year after year, the amount of plastic consumed rises, resulting in an increase in plastic waste. Plastics are used

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in a variety of applications, including automotive and industrial, food and beverage packaging, food distribution, medical delivery systems, water desalination, soil conservation, communication materials, housing, and security systems. With such a wide range of applications, it has contributes to the growth of plastic waste. Plastic production and consumption, as well as the rate at which solid plastic waste is generated, will continue to rise year after year due to the growing demand for plastics in a variety of applications [1].

Globally, approximately 6.5 billion tons of waste plastic and rubber trash are produced each year, and their disposal poses a significant environmental risk due to their slow decomposition rate [2]. Plastic has become an inseparable part of human life. Low strength and density, long life, lightweight, user-friendly design, fabrication capability, and low cost are all factors that have contributed to this phenomenal growth [3]. There are numerous processes in plastic trash management, including the popular 3R concept of reuse, reduce, and recycle. The reuse and the direct recycling of waste as environmentally friendly construction materials have the potential to reduce the environmental burden. PET (Polyethylene Terephthalate), PP (Polypropylene), LDPE (Low-Density Polyethylene), and HDPE (High-Density Polyethylene) are all recyclable plastics (High-Density Polyethylene) [4]. Polyethylene terephthalate (PET) is one of the most abundant plastic wastes because humans generally use it as plastic bottles and food containers.

Plastic waste such as high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC) can be recycled and used as a concrete material, which could help mitigating the effects of plastics, pollution, and global warming [5]. An option to substitute already limited natural aggregates, which are limited in supply, is to utilize plastic trash as a concrete ingredient. Several academics have conducted research on concrete that uses plentiful PET plastic trash as a concrete material in an attempt to decrease waste as a good option for waste management and environmental conservation. Artificial PET aggregates, in place of fine and coarse aggregates, when combined with minerals such as rice husk ash and cement, have the potential to produce lightweight concrete [6]. Concrete research uses PET waste as fibre [7], as a substitute for fine aggregate [8] as a substitute for coarse aggregate [3], [9] and as an additive [10]. Besides, recycled PET bottles can be made into composite bricks [11]. A previous researcher has evaluated the effects of recycled woven plastic sack waste fibers and PET bottle waste on reprocessed aggregate concrete [7]. The results of the research show that a high alkali resistance and no degradation in recycled aggregate concrete have been found in the 90-day experiments with recycled woven plastic sack waste fibers and recycled PET bottle waste. Compared to recycled aggregate concrete without fibre, recycled aggregate concrete with recycled PET bottle waste fibre and Silica Fume (SF) has increased compressive strength by 3.6-9%, splitting tensile strength by 11.8-20.3%, elastic modulus by 16.9-21.5%, and shear strength by 7-15% [7]. Using recycled plastics instead of natural fine aggregate in concrete has been studied before [8].

Researchers have learned about plastic aggregate bond strength and hydration heat. The plastic aggregate's specific gravity and density have been tested. It has also determined elasticity, split tensile strength, and flexural strength. Recycled plastics have replaced 10% of the natural fine aggregate in concrete, increasing compressive strength [8]. A previous study has investigated using waste PET as a plastic aggregate in concrete [3]. Plastic shreds have replaced 5%, 10%, and 20% of the coarse aggregate in concrete. One of the four concrete samples has been devoid of plastic aggregate.

They have tested fresh concrete and all the aggregates.

The specific gravity of plastic waste aggregate is 1.4, and the maximum density is 115 lb/ft3. Increased plastic aggregate density has resulted in a decrease in the density of concrete specimens. Compressive strength and elasticity of concrete containing 10% waste PET have been increased. Tensile strength has ranged between 8% and 11% of compressive strength. The flexural strength of plastic aggregated concrete has been lower [3]. A previously published research has examined the use of a synthetic plastic aggregate as a substitute for Lytag and volcanic lightweight aggregate in concrete [9]. They have studied how replacement level affects concrete's fresh, hardened, and microstructure properties. With increasing replacement level, slump, compressive, splitting tensile, flexural, and elastic modulus have decreased. There has been no effect of the replacement level on either density.

These mixtures have been found to be brittle after peak, whereas the manufactured plastic aggregate mixtures have been found to be ductile. Structures and non-structures requiring moderate strength and ductility can use concrete mixes up to 25% manufactured plastic aggregate [9]. Then, a previous research [10] has chosen PET in order to see if it could be used as an additive in concrete.

The PET has been crushed in order to incorporate it into the concrete. Crushed PET has been used at 5%, 10%, and 15% by weight of standard fine aggregate in concrete. Four concrete examples have been built, with one serving as a control. The compressive strength of the specimen constructed of concrete containing 5% PET has been higher than the other ones. PET aggregate concrete has a lower flexural strength than normal concrete [10]. Previous researchers have reported a novel composite brick composed of cellulose fibers packed in a thin, hermetically sealed plastic block made of recycled PET bottles [11].

Brick is manufactured to offer excellent thermal and acoustic insulation in building walls and, in certain cases, floor slabs. Additionally, the study has discussed the characteristics of cellulose fibres, mortar, and PET plastic, as well as the production method for bricks. With indices of both 12.5 cm and 24 cm thick bricks, they have been numerically analyzed using formulas or software simulation. The compressive, density, flexural, sound reduction, and the thermal properties of the material are investigated.

The thick brick should have a low heat conductivity index and a good noise reduction. Many countries use thermal and acoustic building codes to compare results. This brick's advantages include lower costs, less environmental impact, and easier construction assembly [11]. PET aggregate-based concrete is extremely light in terms of strength, specific gravity, and density [3]. Using recycled PET plastic trash as coarse aggregate as opposed to natural-materials-based concrete may result in a lighter construction [3], [12]. As a result, discarded PET aggregates may be utilized to lower the unit weight of concrete, lowering the dead weight of the structural concrete [3], [12]. Additionally, recycling PET in concrete reduces the need for conventional aggregate, minimizes waste, minimizes pollution, and conserves energy [3], [9]-[12]. PET plastic as a supplementary material in various forms has a variety of impacts on the properties of fresh and hard concrete and warrants more study. [13].

Recycling PET waste using a solution of calcium hypochlorite ($Ca(ClO)_2$) and a solution of hydrogen peroxide (H_2O_2) before mixing it into concrete as a substitute for coarse aggregate can increase the bonding strength between the cement matrix and plastic aggregate, reducing the gap in the interface transition zone, and subsequently providing the possibility of increasing compressive strength, yet decreasing permeability and porosity [14]. The results of the research on concrete made with recycled plastic waste produced by heating PET to boiling temperatures result in artificial aggregates with a smooth and slippery surface, reducing the aggregate's ability to bond to the matrix and resulting in decreased compressive and flexural strengths. Preliminary research indicates that PET can be substituted for Portland cement in standard weight concrete without impairing its mechanical properties [12]. This study aims to reduce solid waste as a waste management solution while protecting the environment. The boiling point heating method results in the formation of an artificial aggregate with a smooth and slippery surface, which lowers the aggregate's binding capability to the matrix. In this study, artificial aggregate is used as coarse concrete aggregate by recycling PET plastic and heating it to the melting point. The petrography, the porosity, and the mechanical properties of concrete made from recycled PET plastic waste at a melting point temperature are described in this work.

This study has limitations in terms of manually manufacturing artificial PET plastic aggregates, both during the plastic heating process and in terms of breaking the lumps into aggregates that resemble natural crushed stone models. As a result, research on machines for producing PET plastic aggregates that can control the boiling point of the plastic as well as break up heated and cooled plastic chunks is necessary. Additionally, research is needed to determine the best method for producing PET plastic aggregates by using chemical substances.

II. Experimental Methods

The method used in this research is experimental in a laboratory. The research variable is a substitute for artificial coarse aggregate in concrete. The artificial coarse aggregate is obtained by recycling PET plastic waste.

II.1. Materials and Equipment

Portland Cement Composite (PCC) cement, sand as fine aggregate (maximum size 4.75), crushed stone as coarse aggregate (maximum size 20 mm), and artificial aggregate from PET plastic waste (5 mm-35.4 mm) have been the materials employed in this research. The equipment used in this research has been a scale, an oven, a sieve, a Los Angeles machine, a mixer, a measuring cup, a cylinder mold with a height of 20 cm and a diameter of 10 cm, a Universal Testing Machine (UTM), a BX51-P Olympus polarizing microscope, and other supporting equipment. Plastic artificial aggregates are obtained by recycling PET-type plastic waste. PET plastic waste is chopped 1-4 cm in size then it is heated in the oven. The temperature used is the melting point temperature of PET plastic. After the plastic is melted, it is removed from the oven and then cooled. The plastic that has been cooled has become solid chunks as shown in Fig. 1(a). The solid chunks are cut into pieces like natural crushed stone with a size of 0.5 cm-2 cm as can be seen in Fig. 1(b).

II.2. Mix Design and Experimental Procedure

The experimental procedure can be seen in Fig. 2. After making the recycled PET plastic waste aggregate, aggregate characterization is carried out before calculating the composition of the concrete mixture.

(a)

(b)

Figs. 1. PET Plastic Artificial Aggregates

The method used in the concrete mix design is the Development of Environment (DOE) method. The results of the concrete mix design can be seen in Table I. The test objects have been made with mixed variations, namely 0%, 25%, 50%, 75%, and 100% PET plastic waste aggregate from the coarse aggregate. Each variation has made 9 samples; 3 samples for compressive strength testing, 3 samples for split tensile strength (f_t) testing, and 3 samples for flexural strength (f_f) testing making the total number of samples 30. Samples have been made using a cylindrical mould size 10 mm × 20 mm. For each sample, a variation is designated as CS (Standard Concrete), C25 (concrete with a 25% substitution of artificial aggregate for PET plastic), C50 (concrete with a 50% substitution of artificial aggregate for PET plastic), C75 (concrete with a 75% substitution of artificial aggregate for PET plastic), and C100 (concrete with a 100% substitution of artificial aggregate for PET plastic). The mixing process is using a mixer.

Firstly, the concrete is poured into a cylinder mould (in fresh concrete conditions). After the concrete hardens completely, the test object is removed from the mould and then treated. Concrete has been treated by immersing concrete samples in a soaking bath for 28 days.

Afterward, it is removed from the water bath and then left for about 20 hours based on ASTM before testing the compressive strength, the split tensile strength, and the flexural strength. The mechanical tests performed have been compressive strength based on ASTM C39 / C39M −12a [15] and split tensile strength based on ASTM C496 / C496M-11[16], while the flexural strength has been based on ASTM C293 / C293M-10 [17].

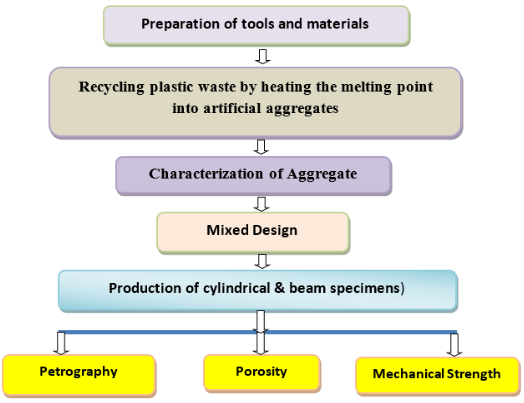


Fig. 2. A diagram of the experimental research process

TABLE I
MIX DESIGN CALCULATIONS FOR 1 m^3 CONCRETE

Sample	Density (kg/m^3)				The Volume of PET Substitution of Coarse Aggregate	
	Cement	Coarse Aggregate	Fines Aggregate	Water	%	kg
CS					0	0
C25					25	161.186
C50	375.75	1070.275	655,79	225	50	322.372
C75					75	483.558
C100					100	644.744

The micro-structural properties have used the petrography test based on ASTM C295 [18]. As demonstrated in Equation (1), the compressive strength ($f'c$) of the concrete is estimated based on the relationship between the size of the sample area and the maximum load. The split tensile strength (f_{st}) test using Equation (2) and the flexural strength (f_f) test have been calculated using Equation (3):

$$f'c = \frac{P}{A} \quad (1)$$

$$f_t = \frac{2P}{\pi LD} \quad (2)$$

$$f_f = \frac{3PL}{2bh^2} \quad (3)$$

where $f'c$ is the compressive strength, A is the area of test section (mm^2), f_t is the splitting tensile strength (MPa), P is the ultimate load (N), D is the specimen cylinder diameter (mm), h is the height of test object (mm), b is the sectional width of test object (mm), L is the length of test object (mm), and $\pi = 22/7$. For the petrographic analysis, the first step is the preparation of the sample to the thin section; both artificial aggregate and concrete using PET plastic artificial aggregate. The thin section is a concrete sample slice ± 0.03 mm thick, which is attached to the glass microscope slide. The stage of making thin sections begins by selecting and marking the parts that represent the concrete components to be analyzed. The next stage is manufacturing a slab by cutting the sample using a coarse blade saw and cleaning it in running water. The subsequent step is to transfer the sample to a medium blade saw cutting tool to make chips measuring 72 × 26 mm or according to the size of the sliding glass used before smoothing the two chip surfaces on the rotating grinder using silicon carbide in sequence from coarse to fine grit, namely 150, 240, 400 and 600 grits. After cleaning with a brush in running water, the chip is transferred to polishing glass to smooth both sides using silicon carbide grit 1000 and 1200. The chip is then cleaned up using an ultrasonic washing machine so that there is no more grit left on the sample. The sample is then dried up on a hot plate covered with aluminum foil at a temperature of 75 °C for ± 2 hours. One side of the sliding glass is coarsened using silicon carbide grit 600 so that the sample adheres properly. The chip surface and the glass slide are then cleaned up with ethanol. Epoxy glue is applied to the surface of the chip and left fully absorbed in the pores. For Petro poxy 154, the resin is mixed with a curing agent with a ratio of 10:1 mm, and then reheated to 100 °C for 60 minutes after it is attached to the sliding glass. The rest of the sample stuck to the sliding glass is cut using a small rock cutter. The slides are grounded by using silicon carbide grits 400 and 600, before being transferred to polished glass using grits 1000 and 1200 to a thickness of ± 0.03 mm. Thickness control is conducted by using a polarizing light microscope by adjusting the color on the interference color chart. Petrography analysis has been conducted by using a BX 51-P Olympus polarizing microscope petrographic at the Geochemistry and Minerals Laboratory at the Department of Geological Engineering, Hasanuddin University. For the porosity test, samples that have been treated for 28 days are removed from the soaking bath and dried in direct sunlight until they reach a fixed weight or dry weight (w_d). After reaching dry weight, the specimen is put into a soaking tub until it reaches a saturated condition or until there are no more air bubbles. Then the test object is removed from the soaking tub and wiped until it reaches the SSD (Saturated Surface Dry) condition. SSD condition test object is weighed to get the wet weight of the test object (w_w).

Then the general porosity is expressed as open porosity calculated based on Equation [19]:

$$p = \{\{(W_w - W_d)/V_b\} \times \{(1/\rho_w)\} \times (100\%)\} \quad (4)$$

where p is the Porosity; ρ_w is the density of water (g/cm^3), W_w is the Wet mass of sample after immersion (g), V_b is the volume of specimen (cm^3), W_d is the dry mass of sample after immersion (g).

III. Result and Discussion

III.1. Petrography of Concrete

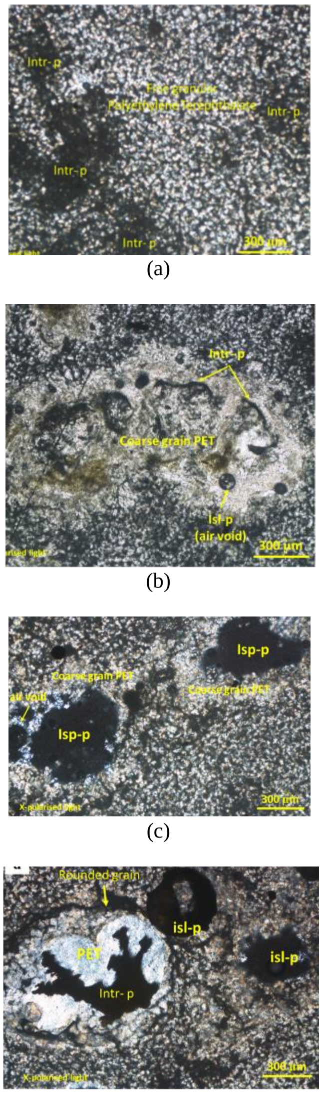
Petrography has been routinely used by geologists for the study of rocks and minerals to characterize and analyze microscopic features. Significant developments have taken place on various techniques used in petrographic examinations of building materials [20], most notably mortar [21], [22], aggregates, concrete [23], and building stone. The optical properties and the microstructural qualities of materials are studied and evaluated using this technology. This paper discusses the petrography of the two types of materials, i.e. PET plastic-made aggregate and concrete using PET plastic-made aggregate.

III.1.1. Petrography of Aggregate Polyethylene Terephthalate (PET)

The plastic aggregate sample on Polyethylene Terephthalate (PET) under a polarizing light microscope is white and the interference color is white-gray order 1.

The grain components consist of two different groups, namely fine-grained that is about 55% and coarse-grained that is about 29%. The visible porosity of the interparticle and interparticle pore to the fine grain is 5% and the coarse grain is about 10%. There is also an isolated pore in the form of air voids measuring 5-100 µm spread over the coarse grain that is about 1%. The spread fine granular group is forming groundmass, well-sorted, in sizes 10-50 µm and form subangular to subrounded. There are dark pores between the dense interparticle measuring 10-100 µm wide and the ones that are sparse in the form of interconnected open up to 200 µm. In some parts the grain has showed tangential contact points up to long so that the pore has been very small <10 µm (Fig. 3(a)). The coarse-grained group shapes fragments sizes 300 - 1500 µm, which form sub-angular spherical to well-rounded shape (Figs. 3(b), (d)).

A floating grain and no contact (Fig. 3(c)) is one in which the large-grain radius is sufficiently bigger than the small-grain radius [24], [25]. This has assured the reducing formation of pores between grains and the bond strength is greater than ellipsoid grains [26]. In the middle, there is an irregular pore measuring 600-750 µm and a fine pore in the size of 10-100 µm shape of sub-rounded. Irregularly shaped voids with an internal surface indicate that they have been formed by water [27]. Opaque interior appearance is due to deposition of fine particles on the surface of the water void. The shapes of the bounding aggregate particles are often visible in the interior of the void and can be interconnected bleed-water voids.



(a) (b) (c) (d)

Figs. 3. Photomicrograph of Polyethylene Terephthalate (PET) artificial aggregate

Air void is an important component of concrete that is useful for increasing the workability of plastic concrete [28], [29], reducing bleeding rates [30], improved freeze-thaw resistance in hardened concrete [31].

However, too much air weakens concrete's compressive strength [32]. Each 1% increase in air, at a given workability, can result in a reduction of 3-5% in compressive strength.

III.1.2. Petrography of Concrete Use PET-Plastic Artificial Aggregate

Observation on the thin section of concrete samples under a polarizing light microscope shows that the cement composition is 60% and granule aggregate is 40%. The relationship between cement and granule is a floating grain and a little is in the form of planar contact (Fig. 4(a)). Cement consists of 12% silica (SiO_2) and 15% calcium carbonate ($CaCO_3$), and a matrix in the form of a grain consist 10% PET (30 - 100 µm), oxidized opaque in the form of fine grain is 5% (<10 µm), 5% pyroxene (50-300 µm), 4% biotite (20-200 µm), 7% isolated pore in the form of void water trapped in cement with a diameter of 5 - 70 µm and 1% intergranular pore sizes 1-3 µm (Figs. 4(b), (c)). The entrained air voids are typically tens to hundreds of microns in size. Entrapped air voids are larger than entrained voids but they have internal surfaces that indicate that they have been formed by air bubbles or pockets. The size and the distribution of air voids have shown to have a significant impact on mechanical properties [33]. Despite having the same density, a narrow range of void sizes can achieve higher strength than the one with a wider pore size distribution [34]. Air entrainment improves the resistance of concrete to damage by forming a network of small, discrete, and closely spaced spherical voids. The spacing factor is inversely proportional to the air content in field concretes, with a tolerance of 1.5% allowed [35].

The aggregate composition in the form of granules consisting of coarse grains sizes 200-1800 µm and 39%.

Coarse grains are composed of PET sizes 300 - 1800 µm and 38%.

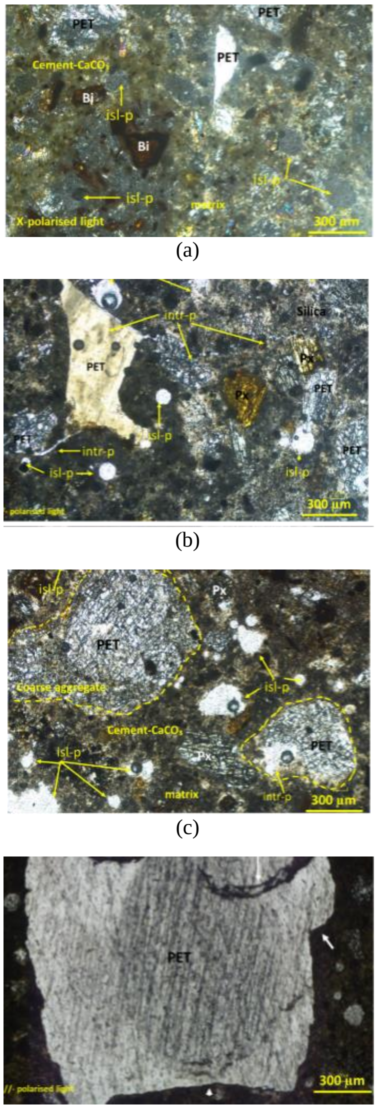
An isolated pore is 1% which is water voids trapped on PET with a diameter of 5 - 50 µm and an intergranular pore of 1% in size 1-3 µm. Polyethylene Terephthalate (PET) is angular to sub-rounded which adheres very well to cement.

It appears that the edges are completely filled with cement and there is no oxidation boundary between aggregate and cement. It is also visible in individual PET coarse that there are cracks filled with cement, This also shows that PET and cement bind adhere well (Fig. 4(d)).

III.2. Mechanical Properties and Porosity of PET Concrete

Concrete porosity is used to measure concrete density.

The mechanical properties of concrete are inextricably linked to porosity.



(a)

(b)

(c)

(d)

Figs. 4. Photomicrograph of Concrete Petrography

Porosity is inextricably linked to the mechanical properties of concrete. Porosity refers to the proportion of pores or empty space in concrete compared to the total volume of concrete. The greater the concrete's density is, the greater its compressive strength is; the greater the concrete's porosity is, the lower the concrete's strength is [36]. Table II, column 3, shows the findings of the porosity score investigation. As can be observed, the greater the proportion of PET aggregate replacement is, the higher the concrete's porosity score is. This is related to the result of petrographic observation of PET-made aggregates. It can be seen that the visible porosity of the interparticle and interparticle pore in the fine grain is 5% and the coarse grain is about 10%. There is also an isolated pore in the form of air voids sizes 5 - 100 µm, which are spread over the coarse grain, which is about 1%. Therefore, there is about 15% pore in PET artificial aggregates. As a result, the cement matrix may be applied to the surface of the artificial PET aggregate, while the residual pores in the rock aggregate remain. As a result, the bigger the quantity of PET artificial aggregate in the concrete is, the higher the porosity score is. The mechanical parameters examined in this study have been flexural strength, compressive strength and split tensile strength. The mechanical qualities of the concrete material determine its quality. These three mechanical qualities are all linked to one another. As a result, mechanical qualities are linked. This portion of the study will look at 1) the mechanical characteristics of concrete manufactured from PET plastic, 2) the relationship between compressive strength, split tensile strength, and flexural strength, and 3) the connection between split tensile strength and flexural strength. It has employed cylindrical concrete specimens such as cast cylinders and drill cores by ASTM C39 [37] in order to estimate compressive strength. By dividing the greatest force obtained during the test by the cross-sectional area of the specimen, the compressive strength of the specimen is computed. Tensile strength and split tensile strength are synonymous [38]. In most cases, split tensile strength is greater than direct tensile strength but lower than bending strength. In the design of structural concrete types, the split tensile strength is used to calculate the length development in the reinforcement and to assess the shear resistance provided by the concrete (ASTM C496) [16]. The Modulus of Rupture, which is measured in psi or MPa, is a measure of flexural strength. The ASTM C293 (Centre-Point Loading) [17] or ASTM C78 (Third-Point Loading) [40] standard test techniques are used to determine the strength. Table II shows the results of the mechanical properties test of concrete utilizing PET plastic artificial aggregate. The mechanical test findings in Table II column 4 reveal that when PET plastic artificial coarse aggregate has been substituted, the compressive strength result has decreased. The lower the compressive strength value is, the more PET plastic artificial coarse aggregate is used. This study supports previous research on concrete made with artificial aggregates made from plastic waste [10], [30]. By substituting PET plastic waste aggregate for concretes, compressive strength and modulus of elasticity can be increased by 10% [3]. According to previous research, treating PET waste with a calcium hypochlorite $(Ca(ClO)_2$ and hydrogen peroxide (H_2O_2) solution can increase compressive strength by 10-30% [14]. This chemical solution has an influence on the coarsening surface of the aggregate, increasing the binding strength between the cement matrix and the plastic aggregate and reducing the gap in the interface transition zone [14].

The split tensile strength (column 5) and the flexural strength (column 6) are shown in Table II. The concrete sample substitute with the greatest split tensile strength and flexural strength is 25 percent artificial aggregate.

The usage of PET plastic artificial aggregate in concrete exceeds 25%, resulting in a decrease in split tensile and flexural strength. According to previous research, incorporating 25% to 75% PET waste as a fine aggregate replacement results in a reduction in compressive strength, tensile strength, and flexural strength [42].

TABLE II
POROSITY AND MECHANICAL PROPERTIES OF CONCRETE USE PET PLASTIC ARTIFICIAL AGGREGATES (PET-PAA)

Sample Name	Artificial aggregates %	Porosity (%)	Compressive Strength $f'c$ (MPa)	Splitting Tensile Strength f_t (MPa)	Flexure Strength f_f (MPa)
(1)	(2)	(3)	(4)	(5)	(6)
CS	0	10.5	17.37	2.14	2.71
C25	25	11.1	15.56	2.35	2.96
C50	50	12.3	14.22	2.25	2.60
C75	75	13.7	12.49	2.15	2.29
C100	100	14.0	10.53	2.04	2.19

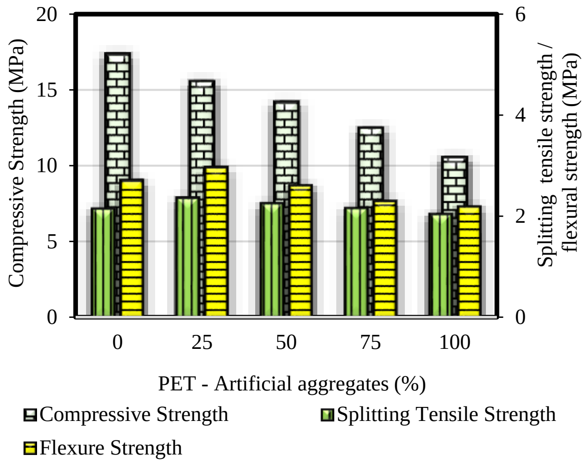


Fig. 5. The comparison between compressive strength, flexural strength and split tensile strength, of Concrete substitution of PET artificial aggregate

Compressive strength, flexural strength, and split tensile strength are all compared in Fig. 5. As illustrated, the bigger the quantity of plastic artificial aggregate in concrete is, the lower its mechanical properties are.

However, there is something interesting in Fig. 5, namely the addition of 25% PET plastic artificial aggregate results in a decrease in compressive strength of 10.41%, an increase in flexural strength of 9.15%, and an increase in split tensile strength of 9.90%, when compared to the mechanical properties of standard Concrete Samples (CS). The mechanical and the durability qualities of concrete are affected by the inclusion of plastic [29].

III.3. The Split Tensile Strength- Compressive Strength Relationship

The compressive and the tensile strengths of concrete are critical in the analysis and design of concrete members. The splitting tensile strength of concrete has been predicted using several theoretical and empirical models that have been established. [43]. The empirical formulas for split tensile strength (f_t) and compressive strength ($f'c$) have been proposed by previous researchers who have used a model similar to the one in Equation (5) [44]:

$$f_t = k\ (f'c)^n \tag{5}$$

where n and k are coefficients, $f'c$ is compressive strength (MPa). The value of n is suggested between 0.5 and 0.85. The relationship between compressive strength (*f'c*) and split tensile strength (f_t) in concrete using PET plastic-made aggregate can be seen in Fig. 6. The relationship between split tensile strength and compressive strength forms a power relationship in Formula (6):

$$f_t = 0.9052(f'c)^{0.3448} \quad (6)$$

The relationship between experimental results of concrete using PET artificial aggregates is similar to ACI 318-99 [45] and ACI 318-14 [46] (Equations (7) and (8)) and Neville 1995 [47] (Equation (9)):

$$f_t = 0.56(f'c)^{0.5} \quad (7)$$

$$f_t = 0.65(f'c)^{0.5} \quad (8)$$

$$f_t = 0.23(f'c)^{0.67} \quad (9)$$

If the relationship line between compressive strength and split tensile strength is observed, it can be noticed the experimental results approach the equations of ACI 318-99 [48] and ACI 318-14 [46]. In more detail, the relationship between the experimental results is between ACI 318-99 and ACI 318-14.

The relationship between compressive strength and split tensile strength in concrete substitution with artificial aggregate made of PET plastic is slightly different from the third model, where the split tensile strength value decreases as compressive strength increases. However, the split tensile and the compressive strength relationship models yield the same power model as the ACI 318-99, ACI 318-14, and Neville 1995 theories. The split tensile strength to compressive strength ratio decreases as the compressive strength of concrete increases.

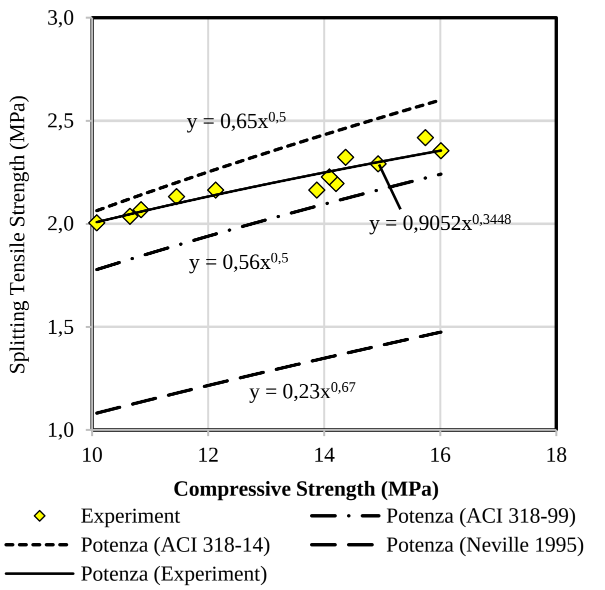


Fig. 6. The compressive strength-splitting tensile strength relationship

As previously demonstrated, both normal concrete and self-compacting concrete will exhibit a decrease in the split tensile strength to compressive strength ratio and an increase in the concrete's compressive strength [43].

III.4. The Flexural Strength-Compressive Strength Relationship of Concrete

The beam bends as a result of the strain caused by the external load. When the load on the beam is increased, the beam reforms and more strain is applied, causing flexural cracks to appear or expand along the beam span.

Structural elements may eventually collapse if the load continues to rise. The results of research into the compressive strength and split tensile strength of concrete made with PET plastic artificial aggregate are depicted in Figure 7. It illustrates the connection between the flexural strength (f_f) and the compressive strength (*f'c*) of concrete made using PET plastic artificial aggregate. Based on Fig. 7, the (f_f) and (*f'c*) relationships form the power equation as in Equation (10). Another relationship stated previously has been suggested by the ACI Building Code ACI-318R-95 (Equation (11)) [49] and ACI 363R-92 (Equation (12)) [42]. The equation formed from the experimental results of concrete substitution artificial aggregate from PET plastic is close to the ACI 363R-92 one [35]:

$$f_f = 0.3654(f'c)^{0.7472} \quad (10)$$

$$f_f = 0.62\,(f'c)^{0.5} \quad (11)$$

$$f_f = 0.94(f'c)^{0.5} \quad (12)$$

The connection between compressive strength and flexural strength in concrete containing PET plastic particles is shown in Fig. 8. This connection is important since it results in the equation $y = 0.4824x^{2.0882}$ with and $R^2 = 0.8293$.

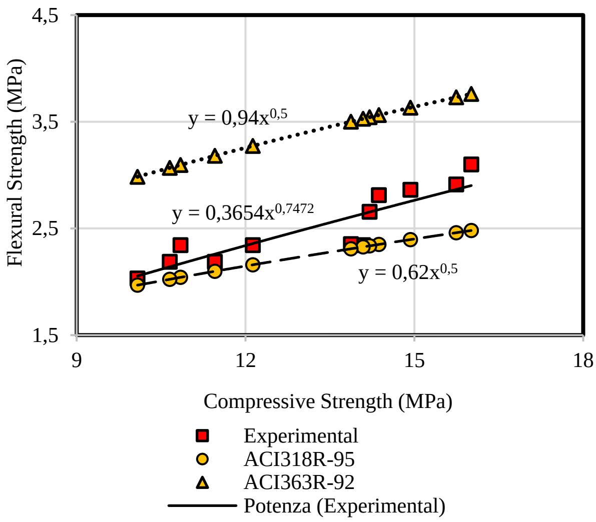


Fig. 7. The relationship between compressive strength and flexural strength

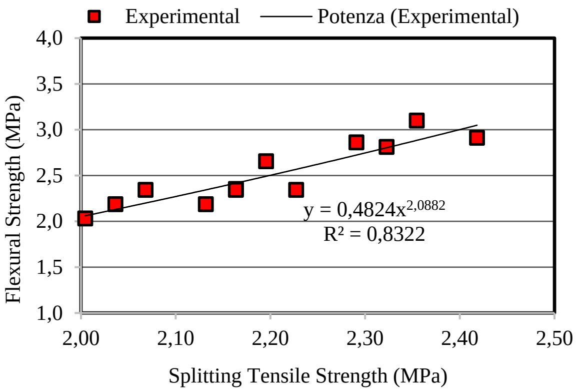


Fig. 8. The splitting tensile strength-flexural strength relationship

The relationship between the tensile and the flexural strengths of concrete made with PET plastic aggregates is a power model. Additionally, Fig. 8 shows that the relationship between compressive strength and flexural strength is significant: the greater the compressive strength is, the greater the flexible value is.

III.5. The Porosity-Compressive Strength Relationship of Concrete

The approximation model for the connection between strength and porosity in current cement materials comprises of multiple equation models [51]. The equation is the exponential power equation with the equation $\sigma = \sigma_0\,(1-p)^K$, linear equation with the equation σ = σ – $K\,p$, logarithmic equation with the equation $\sigma = K\ln(\sigma_0/p)^m$, and the exponential equation with the equation $\sigma = \sigma_0\, e^{-Kp}$ where σ is the compressive strength at porosity (p), σ_0 is the compressive strength at zero porosity, m and K are empirical constants. The porosity and the compressive strength relationship model has been found out by several previous researchers. Balshin's Equation Model ($\sigma = 68{,}74(1-p)^{8.15}$) and Riskewitch's equation model ($\sigma = 74{,}4e^{-8{,}96p}$) is a relationship model from the results of the study of compressive strength and porosity at metal ceramics [52], [53], the power's model $\sigma = 234(1-p)^3$ is an approximation of the relationship between compressive strength and porosity in the mortar [54], and the Hasselman's model ($\sigma = 53{,}45 - 230{,}1p$) is an approach of compressive strength and porosity for different refractory materials [53] as well as a model of the porosity-compressive strength relationship in Self Compacting Concrete using seawater (SCC-Seawater) is $\sigma = 119.6(1-p)^{7.502}$ [36].

Fig. 9 shows the porosity-compressive strength relationship. It illustrates the relationship between porosity (p) and compressive strength ($f'c$) in a material using several of the previously described methods. In addition, Fig. 9 shows the results of the concrete experiment using artificial aggregate from PET plastic to form the exponential power $\sigma = \sigma_0\,(1-p)^K$ as in Equation (13):

$$f'_c = 56.913(1-p)^{10.785} \qquad (13)$$

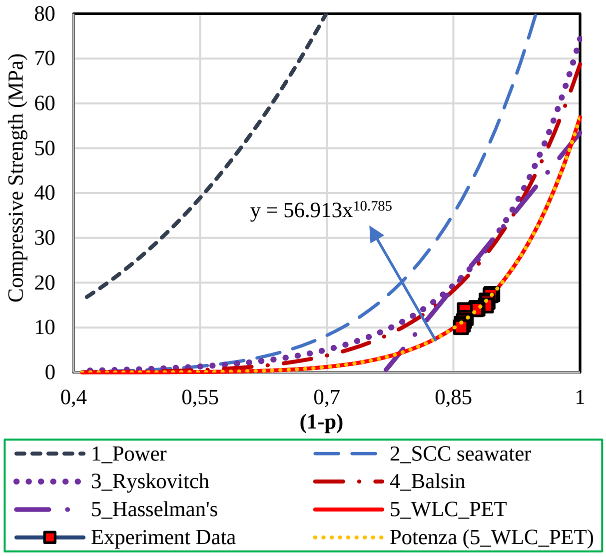


Fig. 9. The relationship between porosity and compressive strength

In comparison to earlier research, Fig. 9 indicates that the connection between porosity and compressive strength in concrete seems to have a greater porosity and a lower compressive strength. Almost all the model methods and the research findings indicate that as porosity increases, compressive strength decreases. The Power model's curve seems to have a lower porosity than the findings of studies on concrete made from artificial PET aggregate, SCC made from saltwater, and the Riskevitch, Balshin, and Hasselman models. The study findings indicate that the connection between compressive strength and porosity follows the Power and Balshin model. Therefore, the compressive strength and the porosity connection curves in the study findings are consistent with model $\sigma = \sigma_0\,(1-p)^K$, despite the fact that the power and Balshin models remain significantly dissimilar. All the prior research' equation models are distinct and their values are very dissimilar, particularly between the experimental findings and the Power model.

This occurs because the resultant model is a simulation of the behavior of various materials, particularly when artificial aggregate is employed, which is lighter and has a high porosity. Additionally, the microstructure and the pore size of the petrography findings have been varied, resulting in a distinct connection between compressive strength and porosity.

The connection or correlation between porosity and compressive strength of concrete is theoretically as follows: the larger the porosity of the test item is, the lower its strength is [37], [41]. The microstructure, the porosity, and the mechanical characteristics of concrete all have an effect on its quality. Reduced porosity correlates with increased mechanical characteristics and phase quality of portlandite (CH), tobermorite (CSH), ettringite and Friedel's salt [36], [55]. As a result, porosity has a significant impact on the compressive strength of concrete. The presence of relatively large concrete particles can also cause porosity, resulting in an inefficient density. Concrete porosity refers to the size of the mechanical characteristics of concrete used to support a construction. The denser concrete is, the better its mechanical properties for sustaining a building are. On the other hand, if the concrete's density is inadequate, its strength is decreased, enabling it to support only light buildings with limited durability. This study still has to be conducted in order to determine the endurance of concrete under load, in extreme temperatures, and in hostile settings (seawater, brackish water).

IV. Conclusion

Based on the petrography test, PET Plastic Artificial Aggregates (PET-PAA) have a visible porosity in the form of interparticle and interparticle pore in fine grains of 5% and coarse grains is about 10%. There is also an isolated pore in the form of water voids sizing 5 - 100 µm spread over a coarse grain is about 1%. In concrete, there are pores both in the cement matrix and on the PET - PAA. matrix in the form of a grain consisting of PET 10% (30 - 100 µm), oxidized opaque in the form of fine grain 5% (<10 µm), pyroxene 5% (50 - 300 µm), biotite 4% (20 - 200 µm), isolated Pore 7% in the form of void water trapped in cement with a diameter of 5 - 70 µm and 1% intergranular pore sizing 1-3 µm. PET artificial aggregates are angular to sub rounded in shape, which adhere very well to the cement matrix. It appears that the edges are completely filled with cement and there is no oxidation boundary between aggregate and cement. It can also be seen that in individual coarse PET there are cracks and pores filled with cement. This also shows that PET and the cement bind and adhere well. The mechanical properties of concrete using PET plastic artificial aggregate have been lower along with the increasing percentage of artificial aggregate substitution.

Split tensile strength (9.90 percent) and flexural strength (9.15 percent) have been increased in light concrete that contained 25% PET plastic artificial aggregate. However, when more than 25% of the aggregate is artificial, the compressive strength, the flexural strength, and the split tensile strength of concrete are reduced. The relationship between compressive strength, split tensile strength and flexure strength in concrete made of PET plastic artificial aggregate forms the Power Model approach $f_t = k\,(f'c)^n$, with k = 0.9052 and n = 0.3448 for the relationship between compressive strength and split tensile strength, and k = 0.9052 and n = 0.3448 for the relationship between compressive strength and flexural strength. Concrete using PET plastic artificial aggregate has a high porosity and low compressive strength. The porosity-compressive strength relationship in concrete using PET plastic-made aggregates can be approximated by the equation $\sigma = \sigma_0\,(1-p)^K$ with $\sigma_0 = 56.913$ and $K = 10.785$.

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