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BEHAVIOR OF CONCRETE MADE OF RECYCLED PET WASTE AND CONFINED WITH CFRP FABRICS

A Thesis
Submitted to the Council of the College of Engineering at University of Duhok as Partial Fulfillment of the Requirements for the Degree of Master of Science (M.Sc.) in Civil Engineering - Construction Materials

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DEDICATION

I Dedicate This Thesis to
Every Person Who Has Offered Me Advice, Love, Care, and Support
Throughout This Study

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SUMMARY

In this study, Polyethylene Terephthalate (PET) plastic waste, which is a type of polymer and commonly used in the manufacture of plastic bottles, has been incorporated into concrete. Therefore, the present study objective is to study the behavior of plastic-containing-concrete by introducing PET plastic waste into the concrete by partially replacing it with fine aggregate. Past-studies showed that plastic-containing-concrete by means of green concrete is typically limited to non-structural applications because of its low strength characteristics. As it is well known, the stability, durability, and safety of the structure largely depend on the characteristics of the concrete compressive strength. Therefore, the present study is an attempt to develop a structural grade class containing plastic waste aggregates with high proportions of substitution, with the presence of CFRP fabrics used to confine concrete.

An experimental study was conducted by casting and testing 117 concrete cylinders and 54 concrete cubes. A concrete mixture was designed in which the fine aggregate was replaced partially by PET waste plastic. The size of the particles was close to that of the replaced sand at a ratio of 0%, 25%, 50%, and with different water/cement ratios of 0.40, 0.45, and 0.55. Physical, mechanical, and durability properties were evaluated which included tests of slump, fresh density, dry density, compressive strength, splitting tensile strength, stress-strain curve, ultrasonic pulse velocity, water absorption, porosity, and thermal conductivity. Laterally, compressive strength and stress-strain tests were performed on cylinders wrapped with one layer of CFRP fabric.

Test results show a degradation in each of the following properties: slump (a decrease of 33-91%), compressive strength (a decrease of 25-77%), splitting tensile strength (a decrease of 20-60%), ultrasonic pulse velocity (a decrease of 17-31%), water absorption (an increase of 41-181%), and porosity (an increase of 35-96%). The degradation of these properties increased with the increase in the plastic aggregate content and the water content. The results showed that with the increase of the plastic aggregate content and the w/c ratio, the fresh and dry densities decreased further, and by using 50% PET, the dry density became less than 2000 kg/m^3, and accordingly, classified as lightweight concrete. Also, by introducing plastic into the concrete, the fracture of a concrete changed from brittle to a more ductile compared to reference concrete. The thermal conductivity decreased significantly (11-47%), and by using 50% of PET, the thermal conductivity became less than (0.71 W/mK), and accordingly, classified as a bearing insulator. In summary, plastic waste can be disposed of by recycling into concrete in specific proportions (not exceeding 25% of PET) for non-structural applications (when the strength of the control mix is within the strength of normal concrete). In contrast, at high rates of

substitution (50% of PET), could be used in insulation lightweight concrete components such as in the case of sandwich panels.

Results showed that confinement had a significant positive effect on the compressive behavior of PET-concrete, in which the enhancement efficiency increased by 8-190% with the increase of the substitution ratio compared to the unconfined samples. Also, one layer of CFRP fabrics raised the ultimate strength of samples that had lost compressive strength to a level close to that of unconfined samples that did not contain plastic (control), since the recovery ratio ranged from 51% to 140%. The lowest strength of 12.21 MPa was recorded for a mixture of 0.55 of w/c with a substitution ratio of 50% for PET and increased to 35.45 MPa (a recovery of 74.27%). Confining is accompanied by an increase in the slope of the stress-strain curve, and the failure has occurred at greater axial and lateral strain values. Also, by increasing the percentage of plastic, the acoustic emission and tear of the CFRP fabric were less severe. Also, all confined cylinders failed due to tensile rupture of CFRP fabrics in the mid-height region outside the overlapping zone. In summary, by using confinement with CFRP fabrics, PET plastic aggregate could be used as a partial substitute for sand with a replacement ratio up to 50% by volume, for structural applications.

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LIST OF SYMBOLS

f'_c, f'_{co}	Compressive strength of plain concrete	f'_{cc}	Maximum compressive strength of confined plain concrete
f'_{cw}	Compressive strength of PET-concrete	f'_{cwc}	Maximum compressive strength of confined PET-concrete
f'_{cr}	Required compressive strength for proportioning	t_{frp}	Thickness of FRP wrapping
f_t	Splitting tensile strength concrete	E_{frp}	Modulus of elasticity of FRP wrapping
f_l	Hoop confining pressure	ε_{he}	Effective strain of FRP at rupture
f_{le}	Actual lateral confining pressure	ε_h	Hoop or lateral (radial) strain of the FRP wrapping
$\varepsilon_{h,rup}$	FRP shell rupture strain	d	Inside core diameter of the confined concrete section
ε_f	Fiber ultimate tensile strain		
k_1	Confinement effectiveness coefficient		
k_ε	Strain reduction factor		
V	Ultrasonic pulse velocity		
V_w	Volume of waste PET		
ε_c	Compressive strain		
k_c	Thermal conductivity for concrete		
R^2	Coefficient of determination		

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing of Materials
CFRP	Carbon fiber reinforced polymer
EU28+NO/CH	28 Member state of the European Union + Norway/ Switzerland
FRC	Fiber-reinforced concrete
FRP	Fiber-reinforced polymer
GBFS	Granulated blast-furnace slag
HDPE	High-density polyethylene
HIPS	High impact polystyrene
HPC	High-performance concrete
HSC	High strength concrete
IEEE	Institute of Electrical and Electronics Engineers
ITZ	Interfacial transition zone
NSC	Normal strength concrete
PET	Polyethylene terephthalate
RC	Reinforced concrete
SCLC	Lightweight self-compacting concrete
SP	Superplasticizers
SSD	Saturated surface dry
UN	United nations
UPV	Ultrasonic pulse velocity
WPLA	Waste polyethylene terephthalate lightweight aggregates

CHAPTER ONE

INTRODUCTION

CHAPTER 1
INTRODUCTION

1.1 General

Concrete is one of the world's most popular and widely used construction materials [1], [2]. Per year, around 12 billion tons of concrete are produced worldwide, which is approximately 1.6 billion tons of cement, 10 billion tons of rock, and one billion tons of water [3], [4]. Besides, the concrete demand is expected to grow to 18 billion tons by 2050 [5], [6]. The concrete industry has a significant environmental impact. But, virtually, the use of concrete cannot be restricted, but there are different approaches to reduce its environmental impact [3, 7].

Moreover, the human lifestyle and the new technology have led to the development of waste products, for which the question of disposal persists. The majority of this solid waste was deposited in waste dump sites; this treatment of waste is unfavorable because most wastes are non-biodegradability and stay in the environment for hundreds and thousands of years [8]. Accordingly, the environmental friendliness of this process decreases.

On the other hand, the principle of adding a substance to another has been used since ancient times to enhance the properties of one of these materials. For example, horse-hair and straw were added to the clay to enhance brick characteristics [9], [10]. Today, fibers in various shapes are used to strengthen the concrete. Concrete confinement is widely used to enhance the strength and ductility of concrete members under compression.

1.2 Plastic Waste

Plastic is one of the 20th century's significant inventions [11]. Worldwide, the utilize of plastic has overgrown since it was first produced for manufacturing utilize in 1920 [12]. According to EuropePlastic [13], plastics can usually be classified into two groups: thermoplastic and thermosetting. Thermoplastics, such as polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polypropylene (PP), and high-density polyethylene (HDPE), that can be frequently reheated, reshaped, and frozen. In contrast, thermosets cannot be reformed after heated and formed, such as epoxy, melamine, silicone, unsaturated polyester, phenolic, and polyurethane.

Due to the advantages of plastics, like the suitability of use and lower cost, there is a growing demand for plastics around the world. As a consequence, the world generated 348 million tons of plastics in 2017, out of which 64.4 million tons were generated in Europe [13]. Figure (1.1) shows the cumulative and recycled amount of plastic waste from 1950 to 2015 and the estimated amount by 2050. In which just around 25% of plastic waste worldwide is recycled, and it is estimated that over 33% of waste produced will be recycled by 2050. Even if this estimate is correct, the volume of non-recycled waste remains highly undesirable and inefficient [12]. As a result, millions of tons of plastic end up every year in oceans and landfills. Moreover, in 2006, the UN environment program predestined an actual presence of 46,000 bits of floating plastic per square mile of sea. Accordingly, this plastic pollution can cause over 100,000 marine mammals and over one million marine birds to die per year [11]. This clearly indicates that the risk of plastic waste is increasing severely.

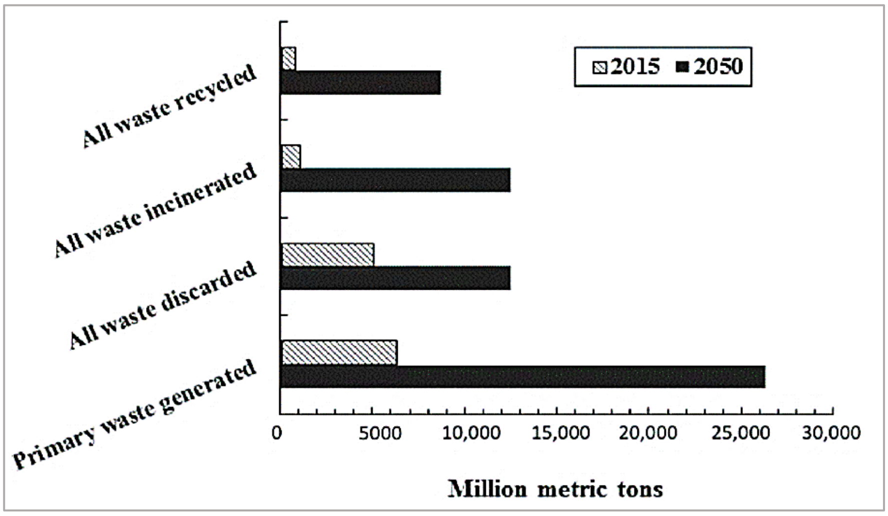


Figure 1.1 Cumulative and recycled amount of plastic waste from 1950 to 2015 and the estimated amount by 2050. Adapted from [14].

The common techniques for treating plastic wastes are varied, like burial, incinerate, and recycling [15]. An undesirable effect of the burial method is the fact that plastic products slowly dissolve and it takes hundreds of years to come back to the natural cycle. While the heat generated during the incineration can be beneficial in the incinerate method however, the burning of other forms of waste such as PET will release toxic gases. So, recycling appears to be the safest path for compliance with the ecosystem and economic gains [15]. Also, to create products with advanced properties than their original form, and one of these products is concrete [16-18]. In which there is a huge potential for recycling plastic waste in green concrete by turning it into construction materials and housing [12], [19]. As a result, the recycling rate will be improving, and demand for natural raw material production will decrease. Thus, the environmental pressure on the concrete sector is reduced, and eliminates the need for natural capital, and thus contributes to sustainable production [2]. For these reasons, many studies have been conducted to use this waste in concrete and it is still ongoing, and the most economical approach is to replace plastic particles with aggregates [8]. However, it is true that the industry offers a large variety of forms of plastics, but studies clearly indicated that not all of them are acceptable as concrete aggregates, as the types of plastic waste that rely on resin and PET have been reported to have the highest utilization rate for concrete production [20-22].

1.2.1 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) is one of the main types of plastics and an associate of the thermoplastic polyester family [23], [24]. The chemical formula for PET plastic is shown in Figure (1.2). Because it consists of terephthalic acid and ethylene glycol, it is known chemically as polyethylene terephthalate or "PET". The molecular formula of PET plastic is $(C_{10}H_8O_4)_n$. Also, it has two types, crystalline and amorphous, and melts at 256-264°C [25].

According to Shubbar and Al-Shadeedi [26], Frigione [27], approximately 30% of PET worldwide, is utilized for the manufacture of bottles. For example, in 2007, the consumption of PET bottles drink was 10 million tons, which is approximately equal to 250 million bottles. This number increases annually by up to 15%. In contrast, the number of bottles recycled is very limited.

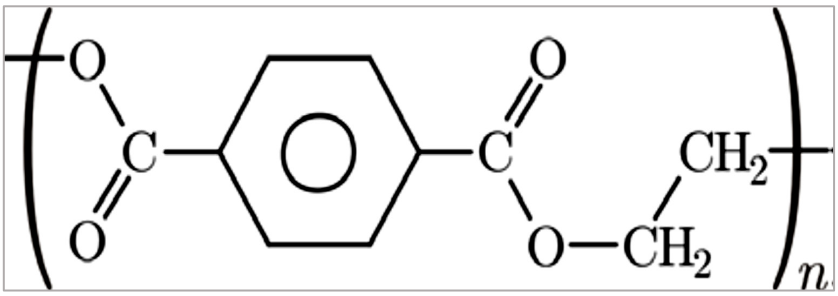


Figure 1.2. The formula of molecular for PET–$(C_{10}H_8O_4)$n. Adapted from [28].

1.3 CFRP Confinement

Confinement is recommended to enhance concrete efficiency [29]. Confining of concrete is accomplished by an effective transverse reinforcement placement. These conducts to a substantial improvement in concrete strength and ductility [29]. For such purposes, many confinement methods are available in the literature, one of the popular confining methods is the use of fiber-reinforced concrete (FRC) fabrics.

Generally, standard concrete has relatively high compressive strength, and on the other hand, there are undesirable properties, such as low tensile strength and low resistance to crack formation. For these reasons, many studies have concluded that concrete confining will confront these problems and enhance the properties of concrete. FRC is described as a composite material, so, the properties of the used fibers contribute to an improvement in the vulnerabilities of standard concrete, like tensile strength [9], [10].

Carbon fiber reinforced polymer (CFRP) is an innovative nonmetallic composite material consisting of a carbon fiber-enhanced polymer resin [30], [31]. It has several excellent features, including high strength-to-weight and stiffness-to-weight ratios, high corrosion resistance, good fatigue behavior, their ability (flexibility) to be formed and shaped to the existing structure, easy to install, long shelf life, light self-weight, high toughness (indicates how much energy a material can absorb before rupturing), anti-high temperature and environmental-friendly characteristics. Figure (1.3) illustrates the typical CFRP structure. CFRP can be made of polymeric materials like polyacrylonitrile, polyvinyl chloride, and cellulose. These precursors are transferred to carbon fibers by a sequence of tensioning and heating processes [31], [32].

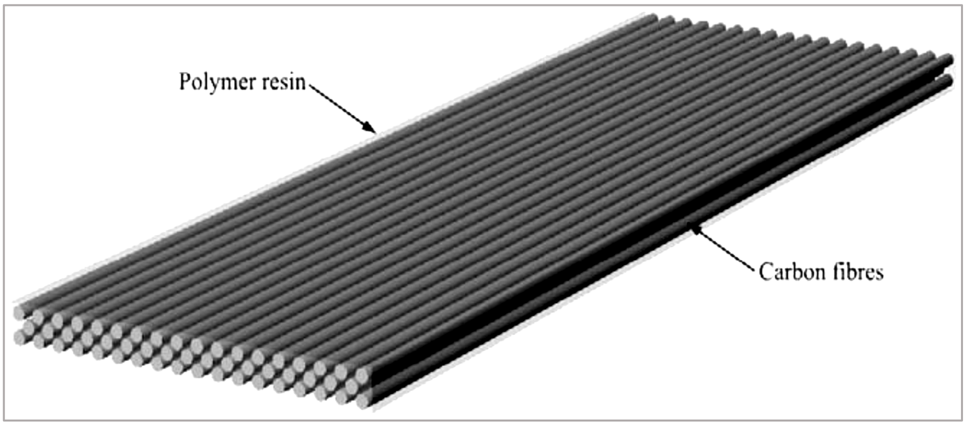


Figure 1.3. Typical structure of CFRP. Adapted from [31].

1.4 Statement of Problem

The flourish of the construction sector results in an increase in demands for construction materials like cement and aggregate. As it is known, in concrete mixes, concrete is constituted by 60% to 80% of aggregate in volume, however, aggregate is a non-renewable source. Continuous quarrying has negative environmental consequences, as well as a lack of aggregate. So, the replacement of aggregate is desirable to reduce pressure on quarries. PET, on the other hand, is a form of plastic waste that grows in lockstep with human waste. Accordingly, this problem causes a lack of landfill in the next few years. Since the recycling of PET lead to a reduction of quarrying activities and can preserve the natural environment. Therefore, the replacement of aggregate by PET is a mutualistic solution to solve both problems. For this purpose, in recent decades, several studies have used waste plastic to substitute aggregates as green concrete (eco-friendly concrete) [33]. However, there are still some issues that previous studies have not addressed or provided solutions to some negative properties such as a decrease in overall mechanical properties when replacing natural aggregates with plastic.

In contrast, over the past four decades, research works have been undertaken regarding the influence of FRP wrappings for certain types of wrapping and loading conditions to advance the strength and ductility of wrapped concrete. However, until now, no work has been executed to find the efficiency of FRP wrapping for concrete members contains PET waste. This study will attempt to bridge this gap.

1.5 Objectives of the Study

The study attempts to achieve the following objectives:

i. Studying the behavior of concrete containing local PET waste as fine aggregate. Also, bridging the gap in some characteristics that previous studies have not addressed or focus on.

ii. Studying the behavior of PET-concrete that confined with CFRP fabrics.

iii. Investigating some relationships between properties of PET-concrete, such as expressions between compressive strength and splitting, UPV, and thermal conductivity.

1.6 Scope of The Study

1. The use of plastic waste type (PET), which has been obtained from plastic bottles only.
2. PET plastic waste has been replaced with fine aggregates by volume in various proportions of 0%, 25%, and 50%.
3. For all concrete mixes, superplasticizers (SP) additive for each mixture was used and only adjust for reference mixtures (0% PET) to obtain a slump (100 ± 10 mm).
4. The concrete mixes are designed with grades of M20, M30, and M40.
5. For curing concrete specimens, different curing ages (7,28, and 90 days) were applied up on the type of test.
6. Studying different characteristics of PET concrete including physical, mechanical, and other properties. Moreover, studying the behavior of CFRP-confined PET-concrete through testing cylinders wrapped with one layer of CFRP fabrics at 90 days from the day of casting.
7. A total of 117 concrete cylinders and 54 concrete cubes with a dimension of (150 × 300) mm, and (100 × 100) mm, respectively, were cast and tested.

1.7 Significance of Study

The use of renewable materials has recently been observed in many sectors because of economic and environmental reasons, in which the utilization of recycled plastic is a significant step toward sustainability. On the other hand, as is well known, FRP reinforcement is used to advance the mechanical properties of the concrete member and structural performance, but little is known about the effect of confining concrete that contains plastic waste. Therefore, the uniqueness of this study is that the behavior of concrete containing PET plastic waste and confined by CFRP fabrics has not been investigated yet. To fill some of the gaps in the field of study, further research on this important topic is required.

1.8 Thesis Outline

This thesis has five chapters, a list of references, and two appendixes, arranged as shown below:

Chapter (1) includes: background on both PET and FRP, statement of problem, objectives, scope, and significance of research.

Chapter (2) includes: reviewing previous researches on the topics of this thesis.

Chapter (3) includes: the characterization of the procedures and research methods used in the study, preparation mixtures, experimental details, material properties, and tests used.

Chapter (4) includes: results and discussion of experimental work and its interpretation. The graphic interpretation is also presented.

Chapter (5) includes: summarizing the general result of current research and offers recommendations for future studies.

References

Appendices:

Appendix A: summary of previous studies on FRP-confined concrete design-oriented models

Appendix B: presents the design of concrete mixtures for this study.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter is divided into two main parts: the first part introduces the incorporation of plastic waste into the concrete, while the second part presents the confinement of concrete by CFRP sheets. Before dealing with the previous studies, this study indicates that the first part presents more detailed characteristics and is much longer than the second part for two reasons. The first reason is that a review-type research has been published from the first part, and the second is the lack of information about PET-concrete wrapped with CFRP sheets.

2.2 Plastic Waste Aggregate

2.2.1 General

The major problem of plastic waste is that it can consist of mixed organic components such as food waste and inorganic waste like paper; this makes the recycling process complicated. However, a potential alternative is to use them as concrete aggregates for different applications where plastic waste pollution would not greatly affect the characteristics of concrete [12], [34]. In most instances, plastic wastes are used as coarse or fine aggregates in concrete. In which the use of these forms of waste in concrete is environmentally friendly [15]. On the other hand, as shown in Tables (2.1) and (2.2), their physical and mechanical properties are significantly different from the natural aggregates. Consequently, various properties of concrete will be influenced by these differences. Based on previous researches, this study will describe most of these characteristics in subsequent paragraphs and sections. Also, this study will investigate most of them in the following chapters.

Table 2.1. Examples of physical characteristics of natural aggregates and plastic aggregates. Adapted from [35].

Type		Dry bulk density (kg/m^3)	Specific gravity (g/cm^3)	Absorbed water 24 hrs. (%)	Reference
Plastic Waste	PET	438.2	1.34	0.09	[36]
	PE	24	1.34	0.10	[37]
	PP	515	0.90	0	[38]
	EPS	30	0.34	0	[39]
Natural aggregate	Sand	1656	2.65	1.80	[40]
	Gravel	1624	2.79	1.32	

* PE: polyethylene; PP: polypropylene; and EPS: expanded polystyrene.

Table 2.2: Typical tensile strength (f_t), elastic modulus (E_c), and thermal conductivity (k_c) of the polymers. Adapted from [41].

Material	Tensile Strength (MPa)	Elastic Modulus (GPa)	Thermal Conductivity (W/mK)
Ref.:	[42]	[42-44]	[44, 45]
PET	55–80	2.1–3.1	0.15
PP	25–40	1.3–1.8	0.12
PE	18–30	0.6–1.4	0.33–0.52
PS	30–55	3.1–3.3	0.105
PVC	50–60	2.7–3.0	0.17–0.21
Limestone gravel	–	70	2.29–2.78
Quartzite sand	–	70	4.45
Cement paste (w/c = 0.5)	–	36–40	1

* PS: polystyrene; and PVC: polyvinyl chloride.

2.2.2 Recycling Options of PET Plastic Waste

In prior researches, specific techniques were used, such as chipping machines or hand cutting, to have the raw substance involved in making up a concrete mixture. Generally, with different forms of plastic additives, the results are different [20], [46].

According to Heredia [24], and Andrady [47], for PET waste, there are two key processing options: closed loop and open loop. The recycled PET waste bottles are used in combination with the virgin material to create a new PET-bottle during closed-loop treatment. While, in the open process, PET waste bottles are used as a raw material for other materials like aggregate. Moreover, closed-loop treatment requires the following:

(i) cleaning of the waste using technology and chemicals to ensure the absence of impurities; (ii) heat treatment at temperatures between 180 and 230 °C; (iii) inert gas reduction; and (iv) finally re-extrusion from 280 °C to 290 °C [24], [48]. In contrast, in the open-loop treatment, waste PET undergoes different processes depending on the purpose of use [24], [47]. Generally, the waste PET is usually sorted, pre-washed, flaked, and pelletized. As shown in Figure (2.1), such process is divided into two parts, upper and lower. The upper part refers to the standard production of PET-bottles. While the lower part refers to the description of current treatments for PET-bottles waste.

In this study, PET-bottles that are used for food preservation purposes will be recycled. Also, the use of a technique, a chipping machine, to involve the body structure of PET in making the concrete mixes. As a result, because of the additional costs, this study will use the open-loop option without using any stages such as pelletizing.

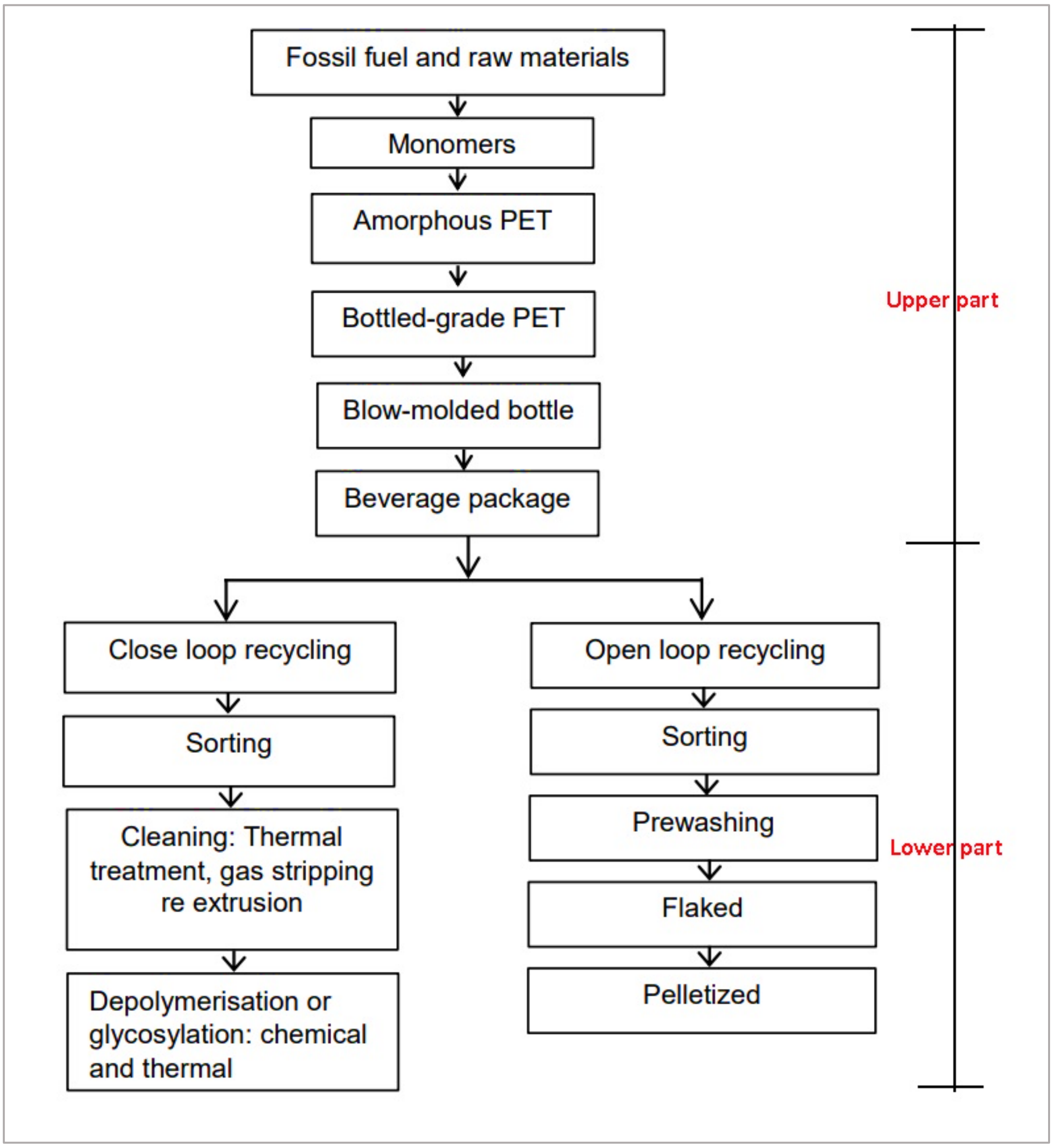


Figure 2.1. Production (upper part) and recycling (lower part) of PET-bottles. Adapted from [47].

2.2.3 Review the Properties of Concrete Containing Plastic Aggregates

Many studies were carried out over the last three decades to study the effect of plastic waste on concrete. In the following sections, this study will review some of these properties, in detail, such as workability, density, compressive strength, and splitting tensile strength. Then, a brief review of the other characteristics will be presented.

2.2.3.1 Workability/Slump

Workability is the consistency of fresh concrete mixtures that identifies how simply it can be homogeneously mixed, set, unified, and finished. While, slump is used to calculate fresh concrete mixes workability or consistency. The effect on workability by replacing different forms and proportions of plastic waste is presented in the following paragraphs. Moreover, some typical information reviewed in the past-studies, are summarized in Table (2.3) and Figure (2.2). As follows:

Al-Manaseer and Dalal [17] addressed the impacts of plastic aggregate on the concrete slump. The authors used angular plastic additives of 13 mm post-consumer size and produced 12 concrete mixes of differing w/c, including the plastic aggregates as a coarse aggregate in the rate of 0%, 10 %, 30 %, and 50%. The authors reported that: (i) once plastic aggregates were added to the concrete, the slump was improved since concrete plastic aggregates of 50 % had a cone slump a little higher than the concrete without plastic aggregates. (ii) the findings of the K-slump consistency reveal a model identical to the slump cone. The authors attributed the reason to that the plastic aggregates do not absorb nor add water to the mixture. Therefore, this non-absorption feature will result in much more free water for concrete mixtures which contains plastic waste aggregates; as a result, the slump increased.

Choi, et al. [49], and Choi, et al. [50] reported the impact of waste PET lightweight aggregates (WPLA) on concrete slump. The concrete mixing percentage was designed to obtain 45%, 49%, and 53% of the w/c ratios and 0%, 25%, 50%, and 75% of the WPLA replacement ratio by fine aggregate volume. In both studies, the slump increased as the waste PET substitution ratio increased. Choi, et al. [49] used granulated blast-furnace slag (GBFS) during the PET smelting process with an internal temperature of 250 °C, with the previously mentioned proportions for PET and w/c. The authors noted that at the addition of (GBFS), the workability increased with an increase in the ratio of PET replacement and w/c ratio. This result is due to (i) the smooth and spherical form of aggregates used in the analysis of waste PET; and (ii) the addition of GBFS resulted in the formation of a composite with GBFS outer layer and PET core.

Batayneh, et al. [51] studied the influence of ground plastic onto the concrete slump. A concrete mixture composed of up to 20 % of plastic waste was proportional to substitute the fine aggregates partially. According to the authors, the following were noted: (i) the slump decreased as the content of plastic particles increases, and (ii) with the key slump value concrete without plastic waste material, slump decreased to 25% (58 mm) for a 20% substitute. The authors attributed that the reason for this decline is due to the shape of the plastic components, i.e., the plastic component has more sharp edges from the fine aggregate.

Ismail and Al-Hashmi [37] utilized plastic waste containers produced up of 80% polyethylene and 20% polystyrene as sand replacements. The percentage of substitution of plastic waste with sand is 0%, 10%, 15%, and 20% and called Pl1, Pl2, Pl3, and Pl4, respectively. With the assistance of the slump test, the authors assessed the workability and observed that with the increase in the proportion of plastic waste, the slump dropped sharply. Slump decreases for Pl2, Pl3, and Pl4, respectively, 68.3%, and 88.33%, and 95.33%, relative to Pl1 of referential concrete. The authors indicate that the cause of the decrease is the irregular shape of the plastic particles.

Tang, et al. [52] studied the influence of polystyrene (PS) on the concrete slump. Mixed concrete proportions were planned in such that the PS replacement ratios are 0%, 20%, 40%, 60%, and 80% by the volume of coarse aggregate. The authors stated that the slump value for fresh lightweight concrete with a coarse aggregate of 20-80 % PS is typically similar to that of standard weight concrete. The authors assigned that the PS coarse aggregate concrete had a shut cellular structure with an insignificant ability to absorb water.

Albano, et al. [15] substituted PET with sand in concrete mixes with two separate w/c ratios of 0.50 and 0.60. The average size of PET particles, small and large, respectively, was 0.26 and 1.14 cm. Fine aggregate was replaced by 10% and 20% of PET for each particle size and 50/50 of both sizes (0.26 and 1.14 cm) combined. A slump test was utilized to evaluate the workability. The authors stated: (i) that the mixtures of 10 % recycled PET have a larger slump in fixed particle size, due to a decrease in the consistency and elasticity of fresh concrete; and (ii) compared with PET particles with size of 0.26 and 1.14 cm, mixtures of 50/50 particle size provide greater slump value, and this indicates a more distribution of PET particles. In addition, PET had an effect on the slump but had a greater impact on the slump as the ratio w/c raised.

Frigione [27] reported a replacement of 5 % of the fine aggregates by weight with the same amount of unwashed PET-bottle waste aggregates. The VeBe test was used to assess workability. The results stated that this ratio of unwashed PET with a cement amount of 300 to 400 kg/m^3 and w/c ratios of 0.45–0.55 have closely the same VeBe time as normal fresh concrete without segregation. The author attributed the reason to small percentages of WPET aggregates that do not impact the water absorption.

Rai, et al. [53] investigated the properties of fresh concrete using virgin plastic waste, where the sand was partially replaced with plastic flakes at rates of 5% - 15% in volumetric, with and without superplasticizer. The authors found that the workability due to substitution was reduced slightly and could be enhanced by about 10% to 15% by adding a superplasticizer. Also, the authors stated, the decrease is due to the irregular shapes of plastic particles, which contributes to lower fluidity.

Silva, et al. [23] studied the effect of replacing plastic aggregate on workability as fine and coarse aggregate separately in addition to the shape of the particles. Plastic aggregates were used in three forms: fine and flaky (PFA), fine and regular (PPA), and coarse and flaky shape (PCA). The percentage of substitution for each type was 0%, 7.5%, and 15% with natural aggregates. The results indicated that the (PFA) and (PCA) decreases workability, while the (PPA) enhanced the workability. This can explain the difference in the internal friction between plastic aggregates of different shapes and bonds.

Safi, et al. [54] studied the possibility of recycling PET plastic waste as an alternative aggregate at 0%, 10%, 20%, 30%, and 50% percentages instead of sand weight in the manufacture of self-compacting mortars. The authors used the flow test to check workability. The authors stated that the self-compacting mortars increased in fluidity with an increase in the amount of plastic waste by up to 50%. The authors related the high fluidity to the smooth surface of the plastic relative to sand and the fact that plastic was difficult to absorb water.

Rahmani, et al. [8] investigated the influence of PET on the workability of concrete. Concrete mixture proportions were designed such that the PET replacement ratios were 0%, 5%, 10%, and 15% per fine aggregate volume. The authors observed that because of the flaky shape of PET, the workability of concrete decreased, which influenced fresh concrete fluidity. Decreased workability became more pronounced as the amount of plastic waste increased. Approximately 42% lost workability as the contents of plastics raised from 0 to 15 %.

Saikia and de Brito [55] investigated the influence of the shape and size of PET plastic particles on concrete workability. The authors used PET to substitute natural concrete aggregates in different quantities, 5%, 10%, and 15% by volume. In addition, three separate types of plastic particles, spherical/cylindrical shape produced by heat treatment pellets called (PP), a flaky coarse size called (PC), and flaky fine size called (PF) were used. The study results show a slight rise in the slump of fresh concrete with the combination of PP aggregate due to smooth surface texture, and a great deterioration (significantly decrease of workability) with the incorporation with PC and PF aggregate volume due to its angular and non-uniform nature, and further decreases if these kinds of aggregate increase its content and size.

Almeshal, et al. [56] analyzed the effects of utilizing PET as a substitution for sand in concrete. A group of six PET-containing concrete mixes was produced as a partial replacement of 0%, 10%, 20%, 30%, 40%, and 50%. The investigators found that adding PET substantially decreased concrete workability. With a 10%, 30%, and 50% PET substitution ratio, the slump had been reduced by 12%, 50%, and 88%, respectively, in accordance with the referential mix. The authors stated that the reason for the reduction was irregular particulate shapes.

2.2.3.1.1 Summary of Workability

The main conclusion that can be drawn from this review section is, there are two parallel views on the workability behavior of concrete containing plastic aggregate. A lower slump value of fresh concrete was observed in the majority of studies due to the introduction of many forms of plastic aggregates, compared to the traditional concrete mix, and when increasing the addition of plastic aggregate, further lowers the slump value. The reasons for the lower slump value of the concrete mix containing plastic aggregate are the sharp edges and angular particle size of plastic aggregate.

On the other hand, in a few studies, an increase in the slump value due to the incorporation of plastic aggregate is also reported. The increase of the slump of concrete mixes due to the incorporation of plastic aggregates is due to the presence of more free water in the mixes containing plastic than in the concrete mix containing natural aggregate since, unlike natural aggregate, plastic aggregates cannot absorb water during mixing.

2.2.3.2 Fresh Density/Dry Density

Density is the weight measured for the volume of concrete occupying one cubic meter of vacuum. In the following paragraphs, the impact of the substitution of particular types of wastes on density is shown. Moreover, some typical information reviewed in the past-studies are summarized in Table (2.3) and Figure (2.3). As follows:

Al-Manaseer and Dalal [17] addressed the impacts of plastic waste aggregate onto the concrete bulk density. The authors used angular plastic additives of 13 mm post-consumer size and produced 12 concrete mixes of differing w/c, including the plastic aggregates as a coarse aggregate in the rate of 0%, 10 %, 30 %, and 50%. The study found that: (i) concrete bulk density decreased by increasing the aggregate volume of plastics, (ii) the concrete density was reduced by 2.5%, 6%, and 13% for concrete contains plastic aggregates of 10%, 30%, and 50%, respectively, and (iii) the density decrease was linearly proportional to the volume of plastic aggregates. The decrease in density was due to the depressing weight of the plastics component.

Marzouk, et al. [57] investigated the use of recycled PET-bottle waste aggregates as a sand replacement aggregate in composite materials for construction products. PET-bottles were utilized as partial and fully sand replacement in concrete compounds. Several volume ratios of sand, ranged from 2-100 %, were supplemented by the same quantity of granular plastic and different sizes of PET aggregates. Their study found that the decrease in bulk density was low when the content of aggregates ranged between 0-30 %, regardless of its size. Moreover, the composite bulk densities began to decline as this volume reached 50% by 1000 kg/m^3. The authors also noted that the bulk density decreases with maximum particle size for the same volumetric proportion. The authors accredited the reason for the decrease to the low bulk density of plastic aggregates.

Ismail and Al-Hashmi [37] utilized plastic waste containers which consist up of 80% polyethylene and 20% polystyrene as sand replacements. The authors stated that the density of fresh concrete that contains 10%, 15%, and 20% of plastic waste aggregates tended to reduce by, respectively, 5%, 7%, and 8.7 %, compared to the reference concrete, because the plastic density was less than the sand density by 69.7%.

Choi, et al. [50] reported the impact of PET waste lightweight aggregates (WPLA) on concrete density. The concrete mixing percentage was designed to obtain 45%, 49%, and 53% of the w/c ratios and 0%, 25%, 50%, and 75% of the WPLA replacement ratio by fine aggregate volume. The authors indicated that the density of concrete mixes has been reduced by raising the volume of the WPLA. The reason for the reduction, according to the authors, was due to the lighter weight of aggregates used in the manufacture of concrete, which was similar to the average but greater than lightweight as compared to normal and lightweight concrete.

Hannawi, et al. [58] investigated the density of both fresh and dry concrete contains PET and polycarbonate (PC) as a fine aggregate. The results showed that both fresh and dry density decreased with the increased volume of plastic aggregates. The dry density of a mixture of 0% plastic aggregate was 2173 kg/m^3, and this density was reduced to 1755 kg/m^3 and 1643 kg/m^3 for a mixture of 50% plastic aggregate for both PET and PC, respectively. These values were below the minimum classification for lightweight concrete structures RILEM-LC2 [59] of 2000 kg/m^3. Thus, it is classified as lightweight concrete. The authors attributed the reason to the plastic's low specific weight (SG).

Rai, et al. [53] investigated the properties of concrete using virgin plastic waste, where the sand was partially replaced with plastic flakes at rates of 5% - 15% in volumetric, with and without superplasticizer. The authors stated that increasing the content of plastic waste decreases both the fresh and dry density of concrete, since when ratio of 5%, 10%, and 15% of the sand were substituted with plastic waste flakes, the fresh density reduced, respectively, 5%, 8.7%, and 10.75%. According to the authors, the result was possibly due to the 70% lower densities of waste plastic than sand.

Rahmani, et al. [8] investigated the influence of PET on the unit weight of concrete. Mixed concrete proportions were designed such that the PET replacement ratios were 0%, 5%, 10%, and 15% per fine aggregate volume. The authors observed that additional pores in concrete would be created because of the narrow and laminar shape of PET particles when a volume of natural sand was substituted in concrete by PET particles of varying gradation. In addition, excess water in concrete samples not participating in cement and water reactions renders several narrow concrete channels and thus leads to additional pores after drying. Therefore, introducing PET particles into concrete and increasing the w/c ratio, contributes to minimizing concrete unit weights.

Saikia and de Brito [55] investigated the influence of the shape and size of PET plastic particles on the fresh density of concrete. With a growing amount of PET incorporated aggregates, the authors observed a reduction of the fresh concrete density. For different forms of PET aggregates used within this study, the authors identified the trend of this density reduction as follows: coarse flaky plastic aggregate > fine flaky plastic aggregate > pellet plastic aggregate. The explanation, according to the authors, is that plastic has a very low density as compared to natural aggregates.

Kumar and Baskar [40] investigated the impact of electronic plastic waste (E-plastic) onto fresh concrete density. Mixed concrete proportions were designed, such that the E-plastic replacement ratios of 0% - 50% per coarse aggregate volume. The authors noticed that an increase of E-plastic of the concrete mixture caused a lowering in the fresh density. The fresh density of 10%, 20%, 30%, 40%, and 50% tends to decrease by 1.10%, 4.87%, 7.58%, 10.70% and 13.58%, respectively, compared to the reference mix. The explanation for this, according to the investigators, is that E-plastic aggregate has a lower density than coarse aggregate, which leads to a drop in fresh density.

Sosoi, et al. [60] analyzed the influence of sawdust and chopped PET-bottles on the density of polymer concrete designed with natural aggregates and fly ash as a filler. Mixed concrete proportions were designed such that the PET replacement ratios of 0% - 100% by aggregate volume of size 0-4 mm (sand). The investigators have found that the density of hard polymer concrete in each of the waste forms is smaller than 2000 kg/m^3. Also, the authors stated that the concrete was of the lightweight type for shredded PET mixes, which ranged between 1703 to 1948 kg/m^3.

Almeshal, et al. [56] examined the effects of utilizing PET as a substitution for sand in concrete. A group of six PET-containing concrete mixes was produced as a partial replacement of 0%, 10%, 20%, 30%, 40%, and 50%. The authors noticed that the concrete density decreased with the increase in the percentage of plastic, leading to lighter concrete. Also, the results showed that the concrete samples of 10 %, 30 %, and 50 % of the PET tend to reduce unit weight by 22.51 kN/m^3, 19.33 kN/m^3, and 16.42 kN/m^3, respectively, compared to a reference mix of 24.02 kN/m^3. According to the authors, the unit weight decreased because of the low plastic density.

2.2.3.2.1 Summary of Density

Irrespective of the type and size of substitutions, the incorporation of plastic as aggregate generally decreases fresh and dry densities of the resulting concrete due to the lightweight nature of plastic aggregate. This is mostly due to the plastic's lower specific weight.

Table 2.3. A summary of some typical details of past-studies related to the workability and density characteristics of plastic-containing concrete.

No	References and Year	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	Characteristics that reviewed	
								Workability	**Density**
1	Al-Manaseer and Dalal [17]	Concrete	PP	Cars bumpers	C.A	10, 30 and 50 vol%	≤ 13 / Angular	✓	✓
2	Choi, et al. [49]	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol%	5-15 / Smooth and Rounded	✓	
3	Batayneh, et al. [51]	Concrete	N.M	Waste plastic	F.A	5, 10, 15, 20 vol.%	0.15 – 4.75 / small Particles	✓	
4	Marzouk, et al. [57]	Mortar	Glass + PET	Waste plastic	F.A	2, 5, 10, 15, 20, 30, 50, 70 and 100 vol.%	Type A: ≤ 5, Type C: ≤2 Type D: ≤1 / Irregular		✓
5	Ismail and Al-Hashmi [37]	Concrete	PS + PET (Mix 80% PET & 20% PS)	Plastic containers	F.A	10, 15 and 20 vol%	Length: 0.15–12 & Width: 0.15– 4 / Irregular	✓	✓
6	Tang, et al. [52]	Concrete	PS	Waste EPS	C.A	20, 40, 60 and 80 vol%	4 / Beads & Granules	✓	
7	Albano, et al. [15]	Concrete	PET	PET-bottles	F.A	10 and 20 vol%	(A) 2.6, (B) 11.4 (C) 50/50% of Both Sizes / Flaky	✓	
8	Choi, et al. [50]	Mortar & Concrete	PET	PET-bottles	F.A	Mortar: 25–10 vol% Concrete: 25–75 vol%	≤ 4.74 / Smooth and Rounded	✓	✓
9	Frigione [27]	Concrete	PET	PET-bottles	F.A	5 wt%	0.1–5 / Irregular	✓	

(continued next page)

10	Hannawi, et al. [58]	Mortar	PET & PC	Industrial Waste	F.A	3, 10, 20 and 50 vol%	PET: 1.6–10, PC: ≤ 5 / N.M		✓
11	Rai, et al. [53]	Concrete	Virgin PET	Industrial	F.A	5, 10 and 15 vol%	N.M / Flaky	✓	✓
12	Silva, et al. [23]	Concrete	PET	PET-bottles	F.A & C.A	7.5 and 15 wt%	(A) 2–11.2, (B) 1–4 / (A) Flaky for C.A, (B) Flaky & Regular Pellet for F.A	✓	
13	Safi, et al. [54]	Concrete	PET	Plastic bags	F.A	10, 20, 30 and 50 wt%	≤0.01/ Annular Cylindrical	✓	
14	Rahmani, et al. [8]	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol%	0.15 - 7 / Flaky	✓	✓
15	Saikia and de Brito [55]	Concrete	PET	PET-bottles	F.A & C.A	5, 10 and 15 vol%	F.A: ≤4, C.A: ≤ 11.2 / (A) Flaky, (B) Cylindrical	✓	✓
16	Kumar and Baskar [40]	Concrete	E-plastic	Computer plastics	C.A	10, 20, 30, 40 and 50 vol%	≤ 12.5 / Flaky		✓
17	Sosoi, et al. [60]	Concrete	PET	Waste plastic	F.A	25, 50, 75 and 100 vol%	0-4 / N.M		✓
18	Almeshal, et al. [56]	Concrete	PET	PET-bottles	F.A	10, 20, 30, 40 and 50 vol%	0.075 – 4 / Irregular	✓	✓

* N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate;

PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; HIPS: High impact polystyrene.

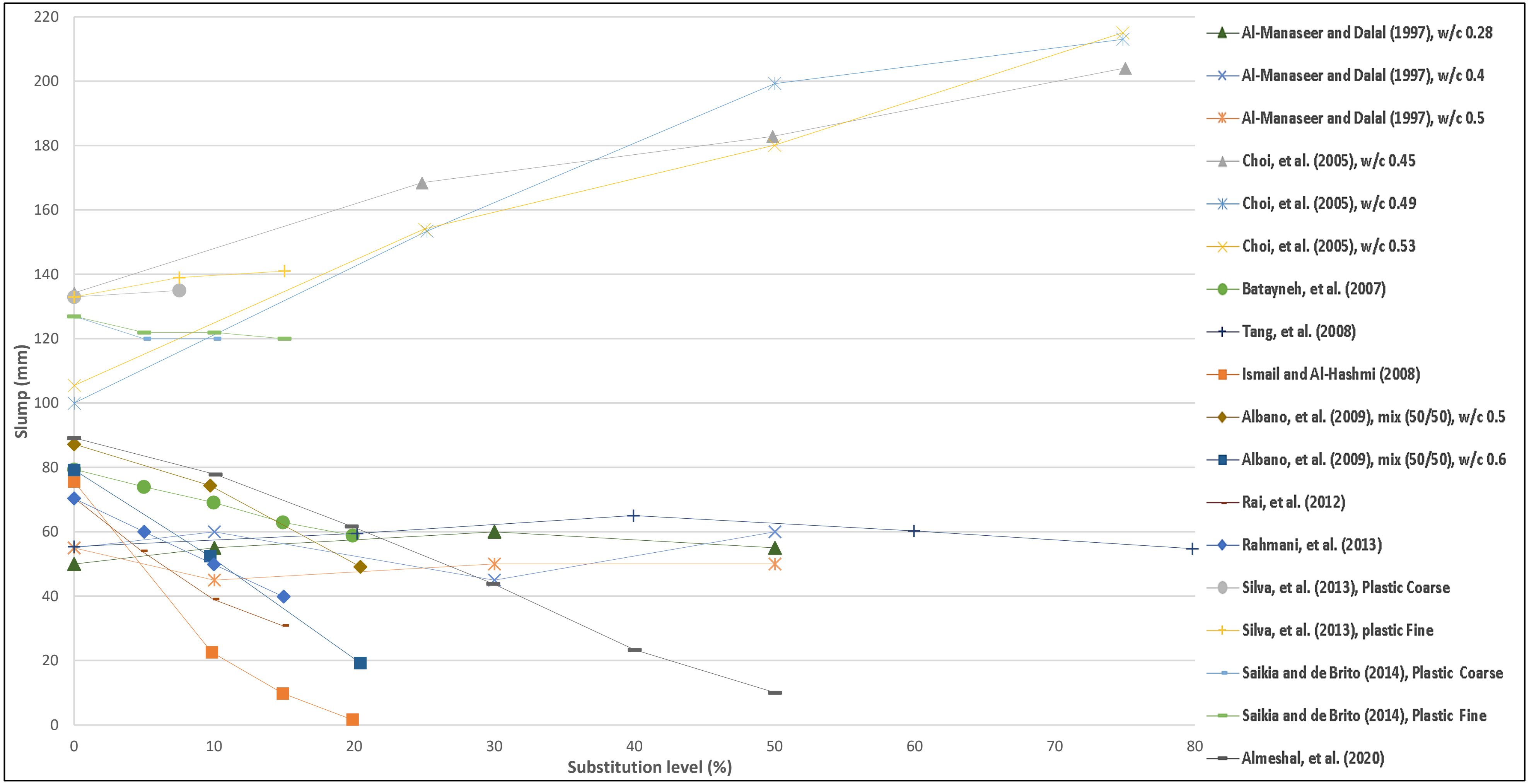


Figure 2.2. Variation of the concrete slump with the plastic aggregate replacement rate.

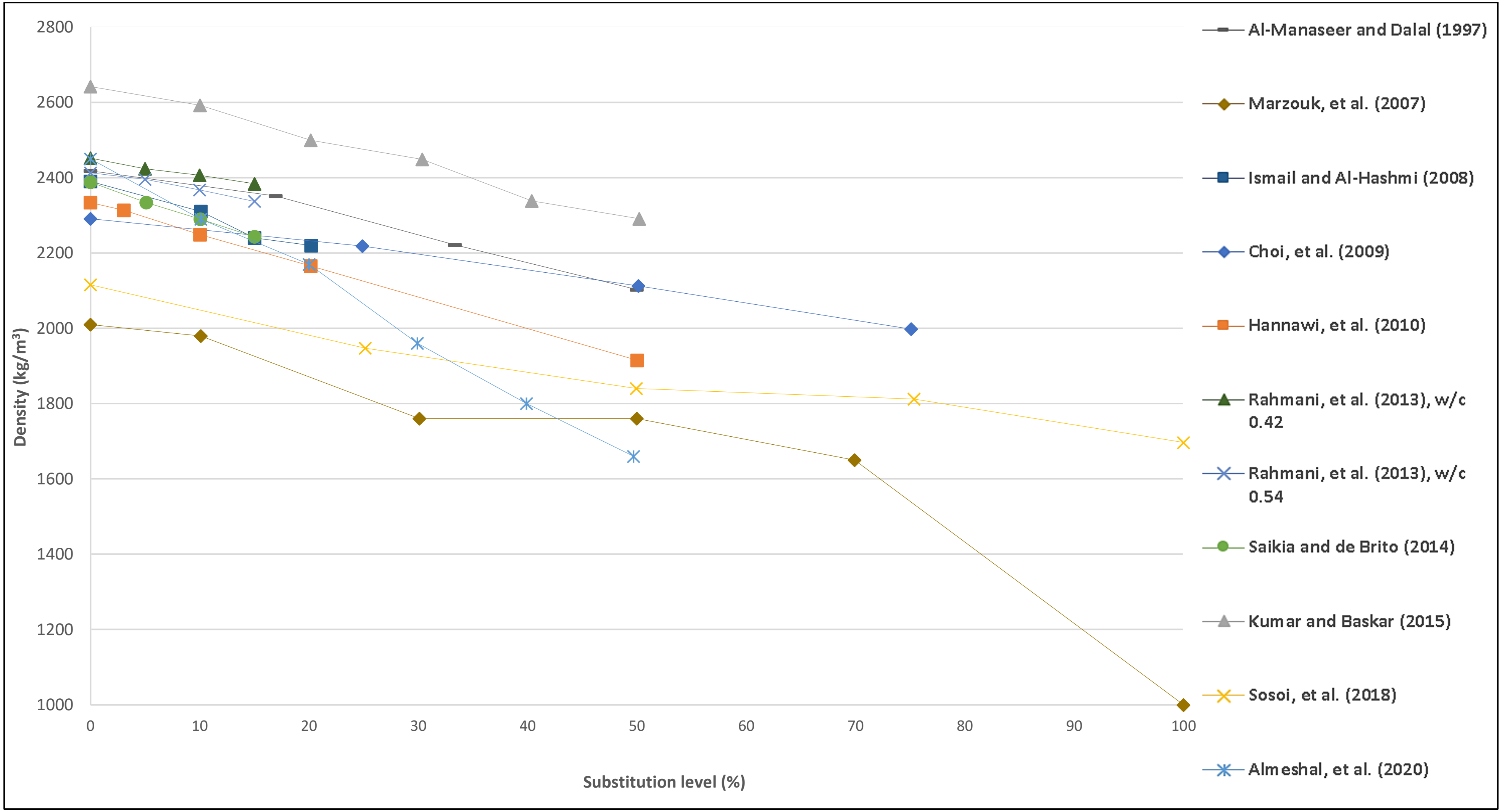


Figure 2.3. Variation of concrete density with plastic aggregate substitution rate.

2.2.3.3 Compressive Strength

Compressive strength represents the capacity of the material to resist pressure applied by the compression machine, as the sample fractured when it passes the limits of compressive stress. The influence on the compressive strength of substitution of different forms of plastic waste is mentioned in the following paragraphs. Moreover, some typical information reviewed in the past-studies are summarized in Table (2.4) and Figure (2.4). As follows:

Batayneh, et al. [51] reported the influence of ground plastic waste onto the concrete compressive strength. A concrete mixture composed of up to 20 % of plastic waste was proportional to substitute the fine aggregates partially. According to the authors, the following observations were noted: (i) the increment of plastic particles decreased the strength characteristics since the compressive strength showed a steep decline until 72% of the actual strength for 20% substitution, while the decrease was 23% for the replacement rate of 5%; and (ii) this decrease was caused because the strength of plastic particles is less than that of natural aggregates. Also, the authors stated that, according to the permissible strength of the structural element to be built, the use of concrete with plastic particles and the proportion of substitution must be controlled.

Marzouk, et al. [57] investigated the use of recycled PET-bottle waste aggregates as a sand replacement aggregate in composite materials for construction products. PET-bottles were utilized as partial and fully sand replacement in concrete compounds. Several volume ratios of sand, ranged from 2-100 %, were supplemented by the same quantity of granular plastic and different sizes of PET aggregates. The authors noted that: (i) shredded plastic bottles to smaller PET particles can successfully be utilized as aggregates for a sand substitute in concrete cementitious composites; (ii) by increasing the substitution ratio from 0% to 50%, the compressive strength of the compounds is slightly decreased; and (iii) replacing sand at a rate under 50% with granulate PET, whose upper granular limit equals 5 mm, does not influence the compressive strength of composites. Also, the authors declared that such composites show to exhibit an appealing, low-cost product with predictable characteristics and to assistance solve some problems of solid waste produced by the manufacture of plastics and to save energy.

Ismail and Al-Hashmi [37] stated that by raising the ratio of plastic waste, the findings indicate a trend to decrease the values of compressive strength at every curing time. This tendency happens because of the decrease in adhesion between the cement paste and surface of the plastic and the rise of the content of plastic waste. Concrete compressive strength provided by substituting 10%, 15%, and 20% of the natural fine by PET aggregate is over the minimum compressive strength needed for concrete structure at 17.24 MPa [61].

Choi, et al. [50] reported the impact of PET-WPLA on concrete compressive strength. The authors stated the following: (i) the replacement of fine PET aggregates decreases the compressive strength; (ii) the amount of average compressive strength drop compared to control concrete for 28 days, regardless of the value of w/c ratio, is 5%, 15% and 30% for WPLA substitution ratio, respectively, 25% and 50% and 75%; and (iii) the structural efficiency, which is the ratio of compressive strength to density, was higher than that of control concrete at 25% substitution ratio, and w/c of 0.49. The authors attributed this effect to the strength of the matrix and the weight of the WPLA.

Albano, et al. [15] stated that: (i) concrete with a 10% PET has a compressive strength that matches standard intermediate strength concrete requirements, which was around between 21 MPa to 30 MPa; (ii) at 28-days, the compressive strength is equivalent to that of 60 days. The authors initiated many reasons for the lower compressive strength of PET-containing concrete compared to normal concrete, such as failure shape, honeycomb formation, poor workability, and particle size. Also, the authors revealed that the decrease in compressive strength was greater with larger flaky PET aggregates than with smaller aggregates.

Kou, et al. [62] studied the effect of replacing river sand with recycled PVC from PVC waste pipes on the compressive strength of lightweight aggregate concrete. Concrete mixture proportions were designed such that the PVC replacement ratios were 0% - 45% per fine aggregate volume. According to the authors, the results indicated that the compressive strength of the concrete decreased by 9.1%, 18.6%, 21.8%, and 47.3% for the concrete mix by, respectively, 5%, 15%, 30, and 45% of the PVC plastic. The authors attributed the reasons for the decline to the following: (i) mismatch of the modulus of elasticity of the PVC particles and the circumference of the cement paste (which led to cracks quickly); (ii) low bonding strength of the TZ, and this weakness increased with increased water resulting from internal bleeding that had accumulated around the PVC particles; and (iii) low level of concrete packing.

Frigione [27] reported a replacement of 5 % of the fine aggregates by weight with the same amount of unwashed PET-bottle waste aggregates. The authors stated that the compressive strength of the resulting concrete is marginally less (not lower than 2%) than that of the concrete containing natural aggregates. The author noted that the effect of rising of curing days from 28 to 365 on concrete compressive strength for both PET and without PET is similar. For high values of w/c ratio and low content of cement, there are significant strength differences between concrete containing normal and PET aggregate. The author explained that this behavior is because of the higher volume of bleeding water in a concrete mixture that contains PET than in the traditional concrete mixture. This water in the PET-concrete mixture is primarily taken position around PET aggregate particles and provides a poorer link between both the matrix of cement and PET.

Hannawi, et al. [58] investigated the compressive strengths of concrete contains polycarbonate (PC) and PET by replacing them with sand in the proportions of 3% - 50%. The authors stated the following: (i) the decrease in compressive strength of PET aggregates was greater than that of PC aggregates for the same amount of substitution; (ii) for mixes 3%, 10%, 20%, and 50% of PET and PC, there was a decreasing in compressive strength of 9.8%, 30.5%, 47.1%, and 69% for PET and 6.8%, 27.2%, 46.1%, and 63.9% for PC, respectively; and (iii) attributed the decrease mainly to the weak bond between the matrix and the plastic aggregate.

Akçaözoğlu, et al. [63] studied the utilization of shredded waste PET as a lightweight aggregate in the mortar. Investigation is carried out on two groups, the first made of only PET aggregate, and the second made of both PET aggregates and sand together. In addition, blast-furnace slag (BFS) is also used as a cement substitute with a 50% replacement rate. The authors stated the following: (i) The compressive strength of mixtures containing PET aggregate and sand together was higher than for mixtures containing only PET; (ii) classified the two groups as well as modified mortars with slag into the category of lightweight structural concrete, and the authors mentioned also, that shredded PET could be useful in designing a ground-earthquake-resistant building.

Rai, et al. [53] investigated the hardened properties of concrete using virgin plastic waste, where the sand was partially replaced with plastic flakes at rates of 5% - 15% in volumetric, with and without superplasticizer. The authors stated that: (i) without superplasticizer, the compressive strength decreased with the increase with the percentages of plastic in all stages of curing, due to the decrease in the bond strength between the cement paste and the plastic aggregate; and (ii) after adding the superplasticizer, the compressive strength improved by about 5%.

Wang and Meyer [64] investigated the influence of high-impact recycled polystyrene (HIPS) in cement mortar as a sand replacement. Concrete mixture proportions were designed such that the HIPS replacement ratios were 10%, 20%, and 50% of sand. The authors stated that the substitution of sand with HIPS in the mortar decreases the compressive strength approximately linearly with the overall HIPS substitution percentage. For HIPS mortar of 10 %, 20 % and 50%, at 28-days, the compressive strength is decreased by 12 %, 22 %, and 49%, respectively. According to the authors, this decline in compression strength is possibly due to the weaker link between both the aggregates and cement paste to the smoother surface of the HIPS granule than the normal sand.

Ge, et al. [65] investigated the influence of sand to PET ratio, gradation, and curing conditions on hardened properties of PET-containing mortar. In addition, an infrared spectrum examination was performed to demonstrate the strength development mechanism. The authors reported the following: (i) the PET mortar with graded sand showed higher strength compared to the single size gradient mortar; (ii) with the increase of sand to PET ratio, the compressive strength could reach 30 MPa, which was 90% higher than its 7 days strength, and (iii) the higher the curing temperature, the greater the strength and crystal quantity.

Silva, et al. [23] observed that the compressive strength decreased with the increase in the content of any type of plastic aggregate. The authors explained the reasons for the decrease to the following: (i) the low bond strength between plastic aggregate and cement paste due to the impermeable nature of the plastic; (ii) the coarser particle size of the plastic aggregate reduces the concrete packing level; and (iii) water that was not absorbed by the plastic aggregate surrounded this plastic, which weakened the bonds.

Ávila Córdoba, et al. [66] studied the effect of both the concentration and size of PET particles on the mechanical properties of concrete. The replacement percentage ranged from 1%, 2.5%, and 5% of fine aggregate. In addition, three sizes of plastic particles were used, which are 0.5, 1.5, and 3 mm. The authors noted the following: (i) the compressive strength is increased by adding different sizes and volume ratios of PET particles; (ii) the highest compression strength was recorded for 0.5 mm PET flakes with 2.5% replacement of fine aggregates; and (iii) the reason is attributed to the fact that the lower of both of concentrations and sizes of plastic particles create less space in the concrete, and consequently the compressive strength increases.

Juki, et al. [67] explored the effect of substituting plastic aggregates (PET) on the mechanical properties of concrete with ratios ranging between 25%, 50%, and 75% of fine aggregates with a different w/c ratio, which is 0.45, 0.55, and 0.65. The authors stated the following: (i) the compressive strength of concrete decreases with the inclusion of plastic aggregates due to the decrease in the adhesion resistance between the plastic aggregate and cement paste, and the plastic does not contribute to enhancing the strength of concrete, as fine aggregate do; (ii) with a 25% substitution rate of PET, the design strength is not less than 25 MPa; and (iii) the lowest compressive strength was recorded for w/c of 0.65, and this is due to the increase in the pore ratio resulting from the non-participation of excess water in the cement reactions, thus producing capillary channels that reduce the compressive strength of the concrete.

Rahmani, et al. [8] studied the impact of PET on the compressive strength of concrete. Concrete mixture proportions were designed such that the PET replacement ratios were 0%, 5%, 10%, and 15% per fine aggregate volume. The authors noted that a 5% substitution of fine aggregates with PET particles provides improved compression performance, since concrete compression strength improves by 8.86% and 11.97%, for w/c ratio of, respectively, 0.42 and 0.52. In contrast, the compressive strength of the concrete decreases upon substitution of 10% and 15% of PET because it works as a buffer to reduce the adhesion between both cement paste and natural aggregates. As a consequence, concrete strength slowly reduces.

Saikia and de Brito [55] stated that the compressive strength declines with the increasing content of PET, independent of the form of PET aggregate or curing period. The compressive strength of concrete for 28 days with 5%, 10%, and 15% of PP was 25%

strength losses compared to reference concrete. The reason was attributed to the reduced contact of cement paste with PET aggregate and, consequently, a poor interfacial transition zone (ITZ); and (iii) PF and PC's strength was less than the PP aggregate.

Azhdarpour, et al. [68] studied the effect of introducing plastic waste particles on the mechanical properties of concrete. Mixing proportions of concrete had been prepared to ensure PET replacement ratios by 0%, 5%, 10%, 20%, 25%, and 30% of the fine aggregate volume. The authors reported the following: (i) substituting 5% - 10% of natural aggregates with PET, the compressive strength of the concrete increased by 39% and 7.6%, respectively, compared to the reference concrete; (ii) inclusion of more than 10% of plastic aggregates reduces the strength properties of concrete; and (iii) The reason for the decrease was attributed to the tendency of the cohesion between the mixed materials to decrease due to the flat shape and smooth surface of the plastic fragments.

Mohammed [69] addressed the effect of PET waste on reinforced concrete (RC) beams, which replaced plastic waste with 5%, 10%, and 15% of the volume of fine aggregates. The bottles were shredded to three sizes of 12 mm, 6 mm, and 3 mm. A mixture of constant weight for each size particle was prepared. The author stated the following: (i) there is a decrease in compressive strength in the range of 12-21% as a result of using shredded PET particles as aggregate in concrete; (ii) the reason for the decrease is the non-homogeneity of concrete in the presence of PET waste; and (iii) the gradation of shredded PET particles does not help reduce the loss of compressive strength. Besides, the author conducted a regression analysis to develop equations (2-1 to 2-4) to calculate compressive strength, maximum compressive strain, and ultimate moment capacity for concrete containing waste PET, and compared them with the results of 242 measurements from other authors with different proportions of PET. The author concluded that the predictions for ultimate moment capacity are accurate, and up to 15% of PET waste can be included to produce RC beams for structural applications. The equations were as follows:

$$f'_{cw} = \frac{1.0387\mathrm{fc}'^{0.953}}{V_{\mathrm{w}}^{0.066}} \qquad 2\text{-}1$$

$$f'_{cw} = \frac{0.494\mathrm{fc}'^{0.85}\gamma_{cw}^{0.143}}{\mathrm{V}_{\mathrm{w}}^{0.066}} \qquad 2\text{-}2$$

$$\varepsilon_{cwu} = 3.573 * 10^{-4}\ (f'_{cw})^{0.913} \qquad 2\text{-}3$$

$$M_n = A_s f_y (d - 0.5a) \qquad 2\text{-}4$$

which f'_{cw} is the compressive strength of concrete containing waste PET in MPa; V_w is the volume of waste PET; f'_c is a plain concrete compressive strength; γ_{cw} is the density of concrete contain waste PET in kg/m^3; ε_{cwu} is maximum compressive strain; M_n is ultimate moment capacity; A_s is area of steel rebar; f_y is yield stress of steel rebar; d is effective depth of the beam section; and "a" is depth of equivalent compressive stress block.

Al-Hadithi and Alani [70] presented a study on high-performance concrete (HPC) compressive strength produced by replacing 2.5%, 5%, and 7.5% of fine aggregate with PET waste. The authors indicated that the compressive strength reduces compared with the reference high-performance concrete (0% PET) with the increases in the PET aggregate for all mixtures and all testing ages. This trend, according to the authors, can be linked to a decrease in adhesive strength between the cement paste and the waste plastic surface. Differences in the shape and size of natural and plastic waste aggregates were also listed as a contributing factor. Also, the authors stated that, in comparison to natural aggregates, PET aggregates cannot react with cement paste, so the ITZ is weaker than the reference concrete, thus reducing the resulting compressive strength. Furthermore, PET aggregates are hydrophobic in nature and can, therefore, limit the water flow required for hydration of cement from accessing the concrete specimen structure during the curing process.

Almeshal, et al. [56] analyzed the effects of utilizing PET as a substitution for sand in concrete. A group of six PET-containing concrete mixes was produced as a partial replacement of 0% - 50%. According to the authors, when the content of plastic in concrete is raised, the compressive strength is reduced. Compared to the control samples during the 28-day curing period, the compressive strength of the replacement ratio 10%, 20%, 30%, 40%, and 50% PET was reduced to 1.2%, 4.2%, 31%, 60%, and 90.6%, respectively. The authors attributed the reason for the decrease in strength to the reduction in the composites bulk density, and also to the reduction in adhesive strength between the cement paste and surface of plastic waste.

2.2.3.3.1 Summary of Compressive Strength

The key conclusion that can be taken from this portion of the literature review is that the compressive strength of all concrete that uses plastic as a partial substitute is most likely to be substantially lower than ordinary or control concrete. The poor bonding between the aggregate with smooth surface and the cement matrix, as well as the presence of voids, becomes much clearer as the percentage of plastic material as partial substitution increases.

Nevertheless, some researchers have managed to obtain satisfying compressive strength, it may be due to the low percentage of plastic content used as well as types of plastic used, which may be an important factor as some plastic materials are tougher and stronger than others. Considering that pretreating plastic aggregate could improve the compressive strength due to improve surface bonding. Still, only low content of these aggregates is suggested to be incorporated in mortar or concrete, with a maximum of 20% aggregate replacement level to avoid excessive strength reduction.

2.2.3.4 Splitting Tensile Strength

Hardened concrete is normally known to withstand a considerable amount of pressure applied both directly and indirectly. Therefore, one goal is to enhance the tensile strength of concrete mixes since concrete is a brittle material. The influence on the splitting tensile strength of substitution of different forms of plastic waste is mentioned in the following paragraphs. Moreover, some typical information reviewed in the past-studies are summarized in Table (2.4) and Figure (2.5), as follows:

Batayneh, et al. [51] reported a study on the influence of ground plastic waste onto the concrete split tensile strength. A concrete mixture composed of up to 20 % of plastic waste was proportional to substitute the fine aggregates partially. According to the authors, the following points were noted: (i) when plastic has been used up to 20% in concrete, the strength of the concrete has been less splitting tensile than ordinary concrete utilizing natural aggregates; (ii) the decrease in tensile strength was not as prominent as in compressive strength; (iii) the use of small plastic quantities in concrete has led to minor improvements to the tensile strength of concrete; and (iv) recommended the use of concrete containing recycled materials such as PET in non-structural engineering applications.

Tang, et al. [52] described a study on the effects of polystyrene (PS) on the concrete split tensile strength. Mixed concrete proportions were planned in such that the PS replacement ratios are 0%, 20%, 40%, 60%, and 80% by the volume of coarse aggregate. According to the authors: (i) the variation of tensile strength of the plastic aggregate concrete increased with the increase in compressive strength but at a decreasing rate; and (ii) the proportion f_t/f_c' increased with increasing the PS coarse aggregate content and with no brittle splitting failure.

Albano, et al. [15] stated that: (i) regardless of the w/c ratio and the size of the waste PET, the tensile strength is lower compared to that of conventional concrete; (ii) the decline is less severe when the 50/50 of both sizes (0.26 and 1.14 cm) combined, and has a greater tendency to decrease at w/c of 0.60; and (iii) the reason for this behavior is the difference in the shape and hardness of the plastic and natural aggregates, also, due to the high porosity.

Choi, et al. [50] stated that the testing value of the split tensile strength of WPLA fine aggregate concrete matched the description for lightweight concrete. The relationship between the compressive strength at 28 days and the tensile splitting strength of PET-concrete has been derived as in Equation (2-5). A similar expression for traditional concrete has been expressed as in Equation (2-6).

$$f_t' = 0.23 * f_c'^{\frac{1}{3}} \tag{2-5}$$

$$f_t' = 1.40 * \left(\frac{f_c'}{10}\right)^{\frac{1}{3}} \tag{2-6}$$

Kou, et al. [62] studied the effect of replacing river sand with recycled PVC from PVC waste pipes on the splitting tensile strength of lightweight aggregate concrete. Concrete mixture proportions were designed such that the PVC replacement ratios were 0% - 45% per fine aggregate volume. Authors observed that: (i) with an increased PVC content, the split tensile strength was decreased similarly identical to compressive strength; and (ii) excellent relation (a direct relationship) was observed between both the 28-days compressive strength and the split tensile strength of concrete that included PVC aggregates as substituted the fine natural aggregate.

Frigione [27] reported a replacement of 5 % of the fine aggregates by weight with the same amount of unwashed PET-bottle waste aggregates. According to the authors, (i) it was noted that split tensile strength reduced a little when unwashed PET-bottle was added in replacement of natural sand in comparison to reference concrete, as does the compressive strength, and it was lower by ranges 1.6–2.4%; and (ii) tensile strength decreases further with height w/c ratio.

Wang and Meyer [64] investigated the influence of high-impact recycled polystyrene (HIPS) in cement mortar as a sand replacement. Concrete mixture proportions were designed such that the HIPS replacement ratios were 10%, 20%, and 50% of sand. According to the authors: (i) the findings referenced that the tensile splitting strength of the mortar is reduced as sand is replaced with HIPS; (ii) the influence on the splitting tensile strength is not effective for a HIPS ratio of 10 %, notably at age 28-days; (iii) the decrease in the splitting strength of the tensile becomes greater as the HIPS rate rises, yet less so at longer curing periods; (iv) for 28-days of curing period, a decrease in the split strength of 1.5%, 11%, and 20% was observed for mortar produced with 10%, 20%, and 50%, respectively; and (v) the influence of the HIPS on the split tensile strength is considerably less than that on the compression strength. This is due to the elasticity of HIPS particles compensates for a little of the material's tensile strength.

Rahmani, et al. [8] studied the impact of PET on splitting tensile strength of concrete. Concrete mixture ratio was designed such that the PET replacement ratios were 0%, 5%, 10.%, and 15% per fine aggregate volume. According to the authors, as the volume of PET particles rises, the tensile strength reduces. The tensile strength decline was respectively 15.9% and 18.06% for the w/c ratios of 0.42 and 0.54, by substituting 15% of sand with PET particles. The increased surface area of PET particles in comparison to sand serves to highlight the deleterious impact of smooth surface texture on bond strength. Furthermore, as the w/c ratio increase, the reduction in splitting tensile strength is more significant.

Juki, et al. [67] observed that the splitting tensile strength of the PET-concrete is typically lower than that of normal concrete with the same w/c ratio. Also, the split tensile strength of plastic aggregates concrete reduces as recycling plastic aggregate increases. The authors attributed the low tensile strength to two reasons, the first is the low density of plastic aggregates, and the second is the low adhesion strength between the binder and the aggregate.

Saikia and de Brito [55] stated that regardless of the ratio and size of PET particles, the tensile strength decreases; the maximum and minimum tensile strength reduced respectively in concrete with PC and PP; and after determining the strength of the tensile cylinders contain normal and granule plastic aggregates, the concrete cylinders contain the flakier PET aggregate was not separated into two fragments, as the flaky plastic aggregate might serve as a link between the two separated components.

Yang, et al. [38] studied the influence of introducing recycled modified plastic polypropylene (PP) particles on the mechanical characteristics of lightweight self-compacting concrete (SCLC). Four substitution rates, 10%, 15%, 20%, and 30%, were adopted for plastic sand by volume. According to the authors, SCLC's split tensile strength is raised by raising plastic content till the amount of sand replacement is up to 15%. In contrast, more the 15% of replacement, the strengths indicate a declining trend because the interface connection between plastic and cement paste exudes and weakens.

Azhdarpour, et al. [68] studied the effect of introducing plastic waste particles on the mechanical properties of concrete. According to the authors, (i) there is an improvement in the tensile strength when applying plastic components up to (5% - 10%). The reason for this behavior is that the tensile strength of plastic components is greater than other concrete components. Thus, plastic enhanced tensile strength, but the higher use of the previous ratios (> 10%) reduces the tensile strength of concrete; (ii) increasing the period of concrete curing also improved tensile strength; and (iii) since PET cannot absorb water, there is no hydration of cement on its surfaces. As a result, by adding additional PET aggregates, the plastic particles will separate from other mortar materials and reduce the tensile strength of the concrete.

Al-Hadithi and Alani [70] reported splitting tensile strength of high-performance concrete (HPC) prepared by replacing 2.5%, 5%, and 7.5% of fine aggregate with PET waste. According to the authors, the concrete tensile strength is significantly less than that of the compressive strength as cracks can spread down tensile pressures. Accordingly, it is a valuable characteristic because cracking in concrete is typically because of the stresses of tension that happen under pressure or environmental changes. Also, the authors stated that concrete failure is driven by micro-cracking, related particularly to the interface area between both the cement paste and the aggregate particles known as ITZ. According to the author, usually, when the PET aggregates substitution level with sand increases, the split strength at the first (2.5% PET) increases, but after a while decreases. For 2.5% PET aggregates amounts, the possibility of interlock of PET aggregates on broken surfaces increases when the load hits the peak because of the flexibility and specific form of the PET particles. However, the splitting tensile strength slowly declines with a raise in the amount of PET aggregates above 2.5 % because of (i) smooth surfaces of PET particles; (ii) poor cohesion between both the PET particles and the cement paste; (iii) the strength of the PET aggregates is lower than the natural aggregates; and (iv) free water at the surface of the hydrophobic plastic aggregates can act as a barrier and prevent the cement paste from adhering to natural aggregates causing a weaker bond between these particles and the cement paste.

Almeshal, et al. [56] observed that the behavior of splitting strength was identical to the compressive strength, as the addition of PET has an adverse impact on the splitting tensile strength of the concrete when the substitute proportion is raised. This result may be due to the variation in rigidity and aggregate form. Also, the authors stated that the reference mixture had a tensile strength of 3.11 MPa, and decreased at substitution of 10%, 30%, and 50% of PET to 2.78 MPa, 2.01 MPa, and 0.45 MPa, respectively.

2.2.3.4.1 Summary of Splitting Tensile Strength

Similarly, to the behavior of compressive strength, the incorporation of any type of plastic aggregate lowers the splitting tensile strength of concrete. The causes for the reductions observed in splitting tensile strength reported in various references were similar to those used to explain the decrease in compressive strength due to the incorporation of plastic aggregate.

This incorporation considerably changes the failure behavior of the resulting concrete. This concrete is more ductile than conventional concrete and it can arrest the cracks generated during mechanical failure of concrete.

Table 2.4. A summary of some typical details of past-studies related to the compressive strength and splitting tensile strength characteristics of plastic-containing concrete.

No.	References and Year	Type of Composite	Type of Plastic Waste	Origin of Plastic Waste	Types of Substitution	Amounts of Substitution	Particle Size (mm) / Shape	Characteristics that reviewed	
								Compressive Str.	Splitting Ten. Str.
1	Choi, et al. [49]	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol%	5-15 / Smooth and Rounded	✓	
2	Batayneh, et al. [51]	Concrete	N.M	Waste plastic	F.A	5, 10, 15, 20 vol.%	0.15 – 4.75 / small Particles	✓	✓
3	Marzouk, et al. [57]	Mortar	PET	PET-bottles	F.A	2, 5, 10, 15, 20, 30, 50, 70 and 100 vol.%	Sort A: ≤ 5, Sort C: ≤2 Sort D: ≤1 / Granular	✓	
4	Ismail and Al-Hashmi [37]	Concrete	PET + PS (Mix 80% PET & 20% PS)	Plastic containers	F.A	10, 15, and 20 vol%	Length: 0.15–12 & Width: 0.15– 4 / Irregular	✓	
5	Tang, et al. [52]	Concrete	PS	Waste EPS	C.A	20, 40, 60 and 80 vol%	4 / Beads & Granules	✓	✓
6	Albano, et al. [15]	Concrete	PET	PET-bottles	F.A	10 and 20 vol%	(A) 2.6, (B) 11.4 (C) 50/50% of Both Sizes / Flaky	✓	✓
7	Choi, et al. [50]	Mortar & concrete	PET	PET-bottles	F.A	Mortar: 25–10 vol% Concrete: 25–75 vol%	≤ 4.74 / Smooth and rounded		✓
8	Kou, et al. [62]	Lightweight concrete	PVC	PVC pipes	F.A	5, 15, 30 and 45 vol%	≤ 5 / Angular	✓	✓
9	Frigione [27]	Concrete	PET	PET-bottles	F.A	5 wt%	0.1–5 / Irregular	✓	✓
10	Hannawi, et al. [58]	Mortar	PET & PC	Industrial Waste	F.A	3, 10, 20 and 50 vol%	PET: 1.6–10, PC: ≤ 5 /N.M	✓	
11	Akçaözoğlu, et al. [63]	Mortar	PET	PET-bottles	F.A	By vol: Binder = 0.5:1 By wt%: 25.64 & 16.95	≤ 4 / Irregular	✓	
12	Rai, et al. [53]	Concrete	Virgin PET	Industrial	F.A	5, 10 and 15 vol%	N.M / Flaky	✓	

(continued next page)

13	Wang and Meyer [64]	Mortar	HIPS	HIPS electronics waste	F.A	10, 20, and 50 vol%	<4 / Irregular	✓	✓
14	Ge, et al. [65]	Mortar	PET	PET-bottles	F.A	1:1, 2:1, 3:1 and 4:1 by vol	≤ 9.5 / Flaky	✓	
15	Silva, et al. [23]	Concrete	PET	PET-bottles	F.A & C.A	7.5 and 15 wt%	(A) 2–11.2, (B) 1–4 / (A) Flaky for C.A, (B) Flaky & Regular Pellet for F.A	✓	
16	Ávila Córdoba, et al. [66]	Concrete	PET	PET-bottles	F.A	1, 2.5 and 5 vol%	0.5, 1.5, and 3 / flakes	✓	
17	Juki, et al. [67]	Concrete	PET	PET-bottles	F.A	25, 50 and 75 vol%	5 / N.M	✓	✓
18	Rahmani, et al. [8]	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol%	0.15 - 7 / Flaky	✓	✓
19	Saikia and de Brito [55]	Concrete	PET	PET-bottles	F.A & C.A	5, 10 and 15 vol%	F.A: ≤4, C.A: ≤ 11.2 / (A) Flaky, (B) Cylindrical	✓	✓
20	Yang, et al. [38]	Lightweight concrete	Modified PP	Waste plastic	F.A	10, 15, 20 and 30 vol%	Length: 1.5–4 / Short column		✓
21	Azhdarpour, et al. [68]	Concrete	PET	PET-bottles	F.A	5, 10, 15, 20, 25 and 30 vol%	(A): 2-4.9 & (B): 0.05-2 / N.M	✓	✓
22	Mohammed [69]	Concrete	PET	PET-bottles	F.A	5, 10 and 15 vol%	12, 6 & 3 (constant weight for each size) / Square	✓	
23	Al-Hadithi and Alani [70]	Concrete	PET	PET-bottles	F.A	2.5, 5 and 7.5 vol%	≤ 4.75 /Flaky, fibre form & pellet	✓	✓
24	Almeshal, et al. [56]	Concrete	PET	PET-bottles	F.A	0, 10, 20, 30, 40 and 50 vol%	4–0.075 / Irregular	✓	✓

* N.M: Not Mention; F.A: fine aggregates; C.A: coarse aggregates; vol.: volume; wt.: weight; PET: polyethylene terephthalate;

PS: polystyrene; PP: polypropylene; PC: polycarbonate; PVC: polyvinyl chloride; EPS: expanded polystyrene; HIPS: High impact polystyrene.

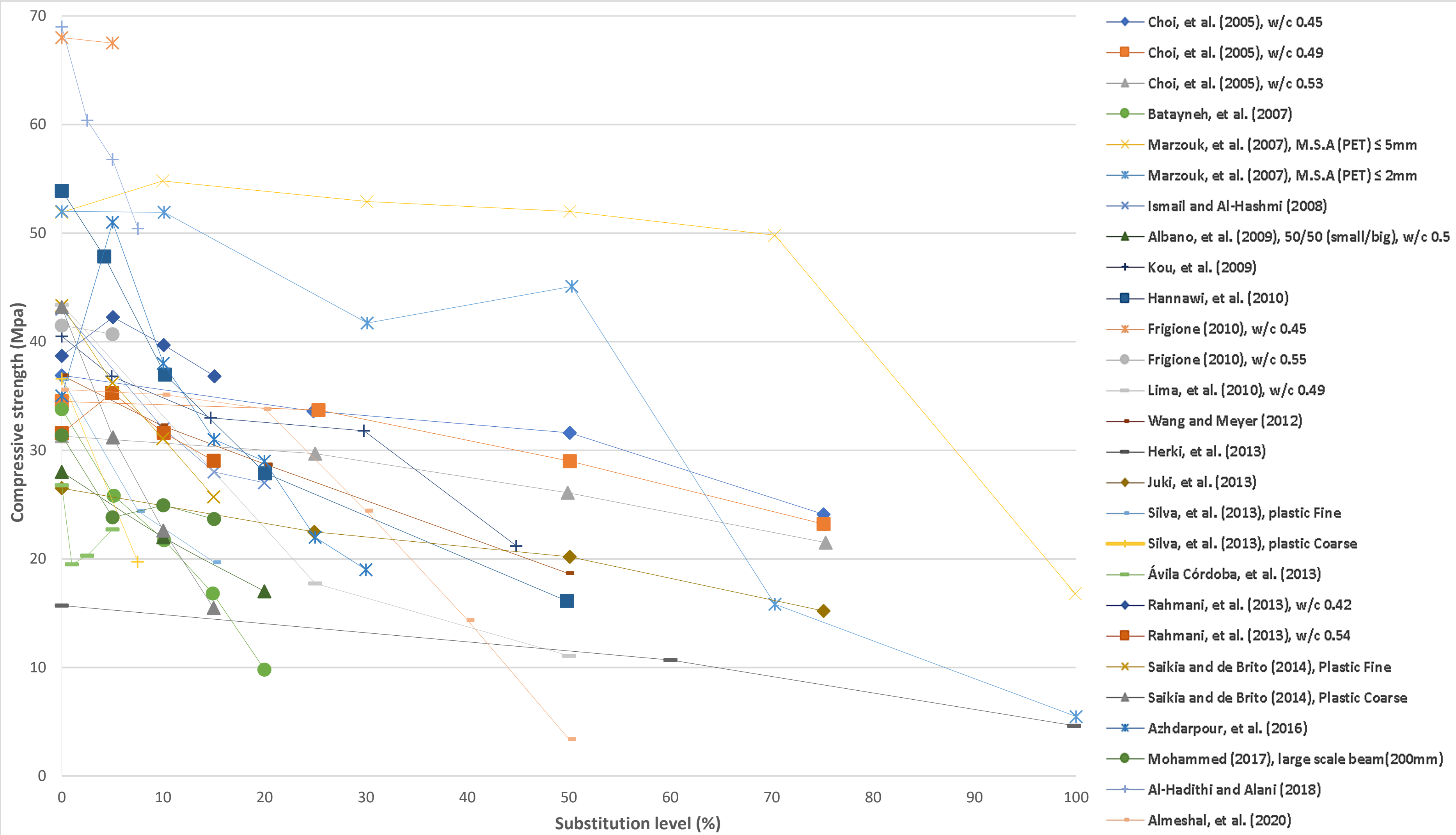


Figure 2.4. Variation of the concrete compressive strength with the plastic aggregate replacement rate.

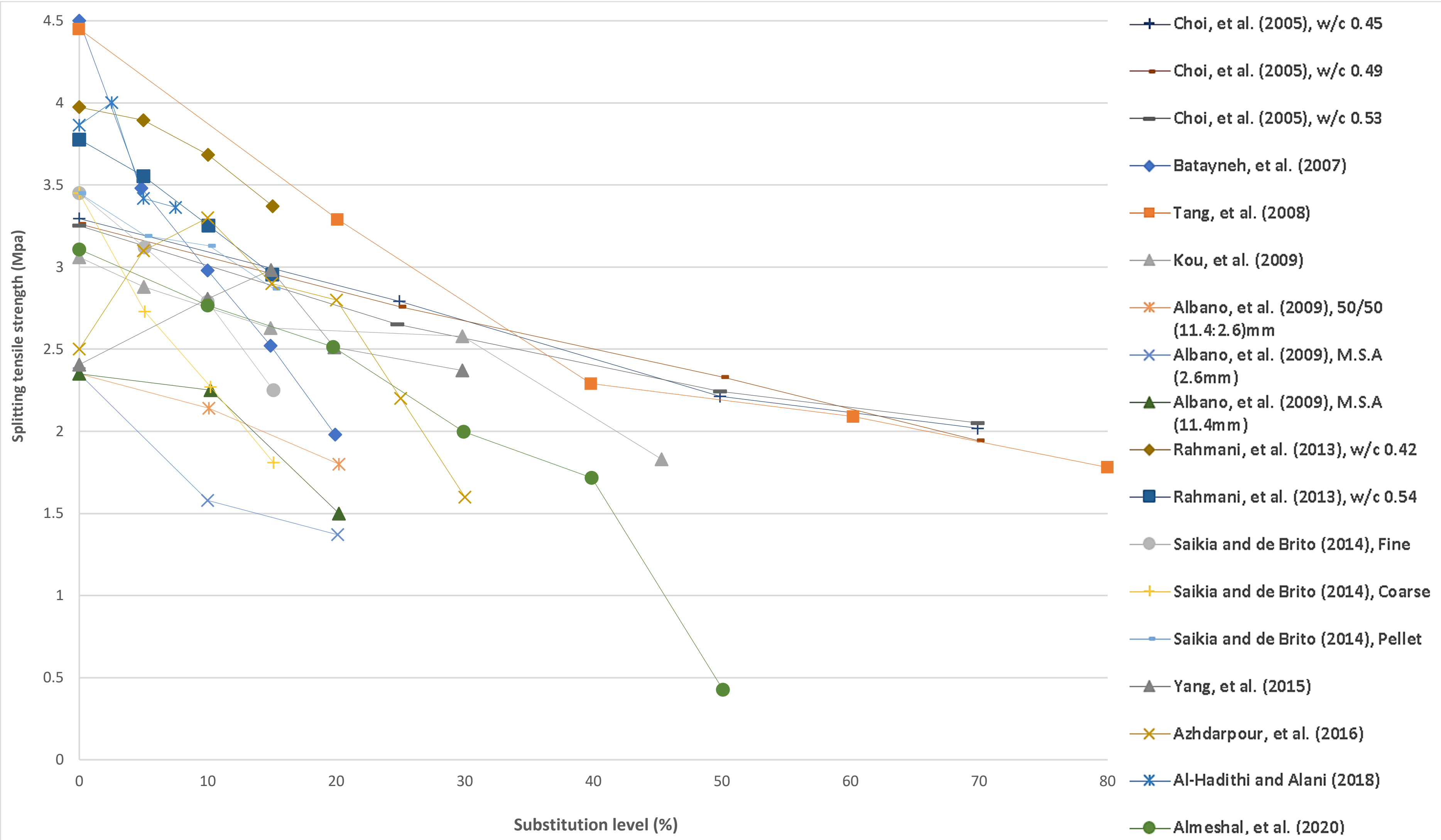


Figure 2.5. Variation of the concrete splitting tensile strength with the plastic aggregate replacement rate.

2.2.3.5 A Brief Review of other Features of Recycled PET in Concrete

In this section, this study will present a brief review of some features that include: water absorption and porosity, stress-strain behavior, ultrasonic pulse velocity (UPV), and thermal conductivity. Also, it should be noted that for the most of the researchers mentioned in these paragraphs, the typical details of their research are mentioned in Tables (2.3) and (2.4).

Water absorption and porosity testing were carried out by different researchers on concrete specimens with plastic aggregates to determine the efficiency of this kind of concrete to prevent corrosion of steel. The water absorption and porosity of concrete containing plastic aggregate increase with a rising in substitution level of plastic aggregates, as natural and plastic aggregates in the concrete matrix do not combine sufficiently, resulting in a porous matrix, as verified by [15, 23, 50, 52, 57, 58, 71]. Albano, et al. [15] declared higher water absorption for PET-containing concrete than natural-aggregate-containing concrete, in which water absorption is further increased with an increase in: PET amount in concrete, increased PET size, and an increasing w/c ratio. The authors concluded that this behavior was due to the variance in size and plastic aggregates shape from the natural aggregate.

Frigione [27] stated that the stress-strain relationship of concrete in which the fine aggregate was replaced by plastic aggregate at 5% was close to conventional concrete. Ge, et al. [65] indicated that the initial curve slope and maximal stress reduced as the ratio between sand and PET increased from 3:1 to 2:1, while the ultimate strain increased. The stress-strain diagrams of [27, 65] show that the peak compressive stress is minimal at a higher plastic replacement rate. Still, the concrete strain, ultimate and corresponding, are higher. In another sense, at a high degree of plastic aggregate replacement, the ductility response will be improved. Still, the peak compressive stress will be lower relative to traditional concrete.

The ultrasonic pulse velocity test (UPV) is conducted to assess concrete structure and homogeneity. UPV of high-quality concrete should be within a scope of 4.1 to 4.7 Km/s [72]. Commonly, the propagation speed of ultrasonic waves in a material count on its porosity; thus, it counts on the elastic and density properties of the material [73]. Past-studies indicate that plastic-contained concrete has lesser UPV because of pores forming and lower unit weight of plastic [8, 15, 73, 74]. Some researchers have found an acceptable scope of UPV for both coarse and fine plastic aggregates. For example, Araghi, et al. [74] evaluated the impact of sulfuric acid curing on the UPV of concrete by 0%, 5 %, 10 and 15% of PET in concrete. The authors found that the UPV was reduced by 32.56%, 32.75%, and 20.7 % respectively. The authors expressed that samples included 15% of PET particles, kept their integrity more, and had higher density.

The thermal conductivity of concrete (k_c) is one of the major criteria to increase awareness of the amount of heat transfer through a conduction. Mostly, the addition of plastic aggregate has a beneficial effect on thermal conductivity as many studies have shown a reduction in the thermal conductivity of concretes with the substitution of plastic aggregates, due to the low thermal conductivity of plastic and increase pores, as claimed by [64, 73, 75-81]. Oumaya, et al. [77] noted that a 50% substitution of PET waste by fine aggregates decreases thermal conductivity by 46%, from 1.28 (W/mK) to 0.69 (W/mK).

2.3 Concrete Confinement

2.3.1 General

The valuable consequence of confinement in enhancing the strength and ductility of concrete under compression has been well established and recognized. Such valuable effects may be limited by the type of loading (static or cyclic) and the shape of the cross-section. For that reason, many methods have been implemented for confining concrete, including:

i. Confinement by steel ties or spirals.
ii. Concrete jacketing by steel tube of various forms.
iii. Tube jacketing concrete in fiber composites.
iv. External fiber composite bonding sheets /wraps or straps on the surface of the concrete.

Each of the above forms of confinement creates the so-called "passive" containment state, in which the wrapping/confining effect of the concrete core is a function of lateral expansion (pressure) as stated by Samaan [82], and Al-Kamaki [83]. Generally, the wish to increase the axial capacity of members under compression through confinement began early last century. Considère [84] has done triaxial testing on Ø 150 mm × 500 mm mortar cylinders and has shown that constant lateral confining pressure of concrete cylinders will dramatically improve their compressive strength. Considère [84] suggested a relationship to forecast the confined concrete's compressive strength that was adopted later by Richart, et al. [85]. This pioneering work was then adopted by other researchers [86-88].

2.3.2 Concrete Confinement by FRP

Once a concrete cylinder is externally confined with FRP composite shell, the fibers in the hoop path resist the concrete core dilation, producing a hoop confining pressure (f_l) uniformly distributed around the circumstance, see Figure (2.6) and the value of (f_l), is immediately affected by the concrete cross-sectional area and the properties of the FRP sheet and can be calculated using Equation (2-7).

$$f_l = \frac{2nE_{frp}\varepsilon_h t_{frp}}{d} \qquad 2\text{-}7$$

Where:

f_l: Hoop confining pressure, (MPa)

n: Number of FRP layers

E_{frp}: Modulus of elasticity of FRP wrapping, (GPa)

ε_h: Hoop or lateral (radial) strain of the FRP wrapping

t_{frp}: Thickness of FRP wrapping, (mm)

d: Inside core diameter of the confined concrete section, (mm)

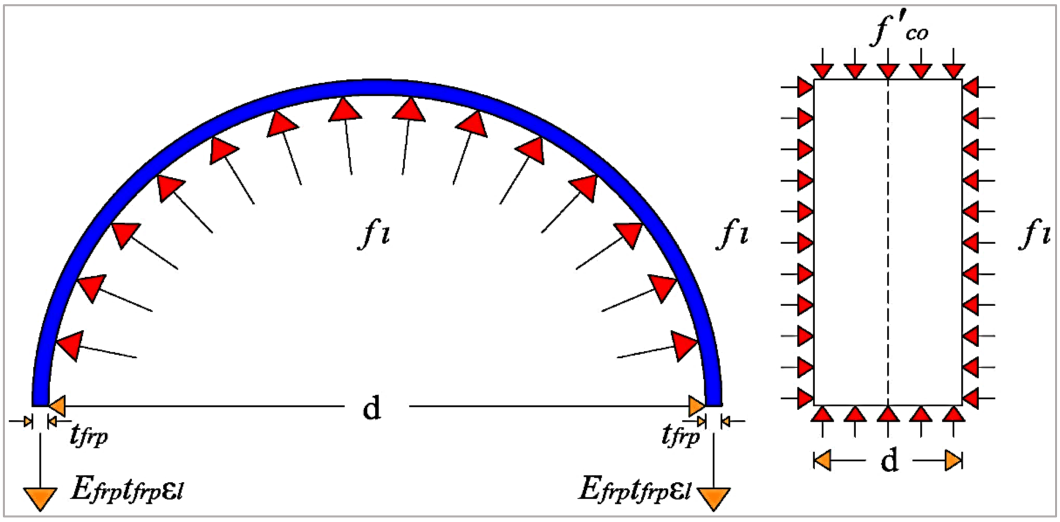


Figure 2.6: Wrapping Mechanism of FRP in circular sections. Adapted from [89].

In fact, as the CFRP sheet ruptures in the hoop direction, the ultimate compressive strength of CFRP-wrapped concrete is obtained [89], [90]. The localization of deformation of the cracked concrete, the overlapping zone, and the FRP wrap curvature are three factors influencing the ultimate strain of CFRP-wrapped concrete and which also influence the computation of effective (actual) lateral confining pressure (f_{le}), see Equation (2-8).

$$f_{le} = \frac{2nE_{frp}\varepsilon_{he} t_{frp}}{d} \qquad 2\text{-}8$$

Where

f_{le}: Actual lateral confining pressure, (MPa)

ε_{he}: Effective strain of FRP at rupture

Pessiki, et al. [91] introduced Equation (2-9) to prove the relationship between FRP shell rupture strain ($\varepsilon_{h,rup}$) to the fiber ultimate tensile strain (ε_f), and a strain reduction factor (k_ε).

$$\varepsilon_{h,rup} = k_\varepsilon \times \varepsilon_f \qquad \text{2-9}$$

The value of the confinement effectiveness coefficient (k_1) evaluates the increase of the strength of the concrete over the (f_l) given by CFRP wraps, as provided by Equation (2-10). This value may either be represented by a non-linear or a constant form. Depending on a regression analysis of the experiment's outcomes, the expression of (k_1) for samples confined with one or more layers of FRP can be proposed.

$$k_1 = \frac{f'_{cc} - f'_{co}}{f_{le}} \qquad \text{2-10}$$

Where:

k_1: Confinement effectiveness coefficient

f'_{cc}: Maximum compressive strength of confined plain concrete, (MPa)

f'_{co}: Compressive strength of plain concrete, (MPa)

f_{le}: Actual lateral confining pressure, (MPa)

Most of the proposed design-oriented models for circular sections adopted a definition that is focused on the steel-confined concrete model suggested by Richart, et al. [85], and Richart, et al. [92] through testing carried out on concrete samples confined under hydrostatic fluid pressure. It was stated that the confined concrete strength at failure (f'_{cc}), can be described as a linear function of (f_l), see Equation (2-11). Richart, et al. [92] claimed that (k_1) is equal to (4.1) (a constant). Most of the experimental results existing in the literature exhibited a linear relationship between the (f'_{cc}) and the (f_l). For simplicity, the design-oriented studies are summarized in Appendix A (Table A.1).

$$f'_{cc} = f'_{co} + k_1 f_l \qquad or \qquad f'_{cc} = f'_{co}\left[1 + k_1 \frac{f_l}{f'_{co}}\right] \qquad \text{2-11}$$

2.3.3 A Review of Previous Studies of Concrete Confinement by FRP

In general, several experimental studies on the impact of FRP confinement on concrete were conducted by [93-97]. The outcomes demonstrated that the most effective confinement was obtained for circular sections, while for square sections, when it is difficult to increase rounding of corners, additional confinement can be achieved by wrapping additional layers.

Since 1980, many investigations have been undertaken with the aim of understanding and modeling the compressive behavior of FRP-confined concrete at ambient temperatures. Consequently, many stress-strain models have been developed or suggested by several authors (see Appendix A). Most current models can be categorized into two different categories [98]; namely, design-oriented models (empirical models), typically presented in simple algebraic form (i.e. clear statements based on experimental outcomes regression) and analysis-oriented models suitable for iterative numerical analysis (i.e. based on triaxial compression concrete content models).

The strength prediction of concrete made of recycled waste PET and then confined with CFRP fabrics needs further consideration in the future. Almost all of the existing models in the literature probably will be insufficient to predict the behavior of the tested cylinders in this study. The reason for that is, such models presented in the literature have been developed based on normal or high strength concrete without the presence of PET by means of green concrete. For this reason, the existing models have been relocated to Appendix A (Table A.1).

2.4 Summary

Chapter two of this study has presented first, an in-depth literature review on the properties of concrete made of recycled PET waste replacement from plastic bottles. Based on such review, a significant decrease has been observed in the overall mechanical and physical properties of concrete when PET is used as fine aggregate in concrete by means of green concrete. Generally, concrete that contains PET can be used for non-structural purposes that do not require high compressive strength as it acts as light concrete. This has been considered as a gap in the literature to find a proper solution to how to use concrete made of recycled PET for structural purposes as well. Furthermore, this review has considered experimental and design-oriented models (empirical models) that have been undertaken on concrete members under compression and confined with various types of FRP composites (see Appendix A). Most of the studies found in the literature were conducted on plain cylinders without considering the effect of CFRP fabrics for enhancing concrete properties incorporated PET waste under axial compression. Such a gap in the literature was found to be a relevant area of study that needs more investigation. The literature review indicates the following matters that require further investigation, and which will address in this thesis:

i. Some properties have not been adequately covered in previous studies of PET-concrete, such as water absorption, porosity, and thermal conductivity, especially for high percentages of PET, so this study will bridge this gap. In addition, compare the behavior of concrete with PET as fine aggregate, which is obtained from local materials, to previous studies.

ii. As observed in the literature, the strength of compression members can be improved significantly using CFRP wrapping. However, these wrappings have not been applied to PET-concrete, and their behavior together is not known. Therefore, this study will bridge this gap by confining concrete made from recycled PET waste using CFRP fabrics.

iii. The design-oriented models in the literature were able to predict the behavior of normal and high strength concrete successfully as stated by many researchers, see Appendix A (Table A.1). Such models need to be evaluated in the future to check their capabilities to predict the strength and strain at peak load of CFRP-confined concrete taking into account the presence of recycled PET in the concrete.

CHAPTER 3
METHODOLOGY

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter introduces the experiments program and the materials used to explore the possible use of recycled plastics as aggregates in concrete mixtures and evaluate confinement behavior with the CFRP layer. The following sections explain the test methods, descriptions, and equipment used to assess concrete properties.

3.2 Materials

3.2.1 Cement

The ordinary Portland cement (CEM I 42.5R) with the brand name (Tasluja) was used in this study. The chemical composition, physical and mechanical properties, comply with the Iraqi standard specification (I.O.S.) (No. 5/1984) [99], as shown in Tables (3.1), and (3.2), respectively. Furthermore, cement packaging weighed (50 kg) and was stored in the lab room to prevent moisture from the air.

Table 3.1: The chemical properties of ordinary Portland cement *

Chemical Requirements		**Test Result**	**Limitation** **(I.O.S.) (No. 5/1984) [99]**
SO_3	%	2.24	2.5 if $C_3A < 3.5$ 2.8 if $C3A > 3.5$
SiO_2	%	19.11	–
Al_2O_3	%	6.42	–
MgO	%	3.82	< 5.0
Fe_2O_3	%	3.73	–
CaO	%	66.26	–
C_2S	%	19.91	–
C_3S	%	50.40	–
C_3A	%	7.67	–
C_4AF	%	10.03	–
Insoluble residue	%	0.96	Not more than 1.5%
Loss on ignition	%	2.2	Not more than 4%
Lime saturation factor	%	0.91	0.66–1.02
Chloride Content	%	0.01	–

* This test was carried out by the quality control department at Tasluja cement factory.

Table 3.2: The physical and mechanical properties of ordinary Portland cement *

Physical & Mechanical Requirements	**Test Result**	**Limitation (I.O.S.) (No. 5/1984) [99]**
Fineness (Blaine)(cm^2/g)	3470	Not less than 2300
Initial setting time (minute)	190	Not less than 45 min
Final setting time (minute)	240	Not more than 600 min
Compressive strength at 3 days (MPa)	25	Not less than 15 MPa
Compressive strength at 7 days (MPa)	35	Not less than 23 MPa

* This test was carried out by the quality control department at Tasluja cement factory.

3.2.2 Water

Generally, water that is satisfactory for drinking is also suitable for use in concrete. In all concrete mixes and for curing of specimens, drinkable tap water and at laboratory temperature without salt or chemicals, were used. The water source was the concrete laboratory in the College of Engineering/University of Duhok.

3.2.3 Coarse Aggregate

Natural crushed aggregate supplied from (Sejie) region in Duhok city was used for preparing mixes, with the nominal maximum size passing from the sieve of (19) mm, as shown in Figure (3.1). The gravel was cleaned and washed with water several times and allowed drying in the air. Besides, properties of this aggregate, as shown in Table (3.3), that included sieve analysis, specific gravity, absorption, and dry-rodded density, conducted according to ASTM C136 [100], ASTM C127 [101], ASTM C127 [101], ASTM C29 [102], respectively. Also, these properties conform to the (I.O.S.) (No.45/1984) [103].

Table 3.3: Grading test and physical properties of coarse aggregate.

Type of test Grading test	**Results**	**Limitations (4.75-19) mm** (I.O.S.) (No.45/1984) [103]
Sieve size (mm)	% Passing	The limits of cumulative passing (%)
25	100	100
19	97	90–100
9.5	44	20–55
4.75	5	0–10
2.36	0	0–5
Physical properties		
Fineness Modulus (F.M.)	6.58	–
Specific gravity (SSD)	2.67	–
Absorption	0.68 %	–
Bulk Density(kg/m^3)	1540	–

3.2.4 Fine Aggregate

In this study, the natural sand of (Khabour) region was used in concrete mixes. The sand was dried first, then passed through a 4.75 mm sieve, as shown in Figure (3.1). Besides, properties of this aggregate shown in Table (3.4), which included sieve analysis, specific gravity, absorption, and dry-rodded density, conducted according to ASTM C136 [100], ASTM C127 [101], ASTM C127 [101] and ASTM C29 [102], respectively. Also, these properties conform to the (I.Q.S.) (No.45/1984) (Zone 2) [103].

Table 3.4: Grading test and physical properties of fine aggregate.

Type of test **Grading test**	**Results (Zone 2)**	**Limitations** **(I.Q.S.) (No.45/1984) [103]**			
Sieve size (mm)	% Passing	Zone 1	Zone 2	Zone 3	Zone 4
10	100	100	100	100	100
4.75	100	100–90	100–90	100–85	100–95
2.36	80	95–60	100–75	100–85	100–95
1.18	65	70–30	90–55	100–75	100–90
0.6	50	34–15	59–35	79–60	100–80
0.3	19	20–5	30–8	40–12	50–15
0.15	5	10–0	10–0	10–0	15–0
Physical properties					
Fineness Modulus (F.M.)	2.81	–			
Specific gravity (SSD)	2.7	–			
Absorption %	1.14	–			
Bulk Density (kg/m³)	1634	–			

Figure 3.1: Sieving of aggregates: (a) coarse; (b) fine; and (c) PET.

3.2.5 Plastic Waste Aggregate

3.2.5.1 Preparation of Plastic PET Aggregate

In this study, PET particles, as shown in Figure (3.2), are prepared by grinding PET waste bottles. These PET particles were produced, as shown in Figure (3.3), through the following steps:

a) The Light plastic factory [104] supplied this study with PET bottles (type BC210 [105]).

b) Remove the bottle cap.

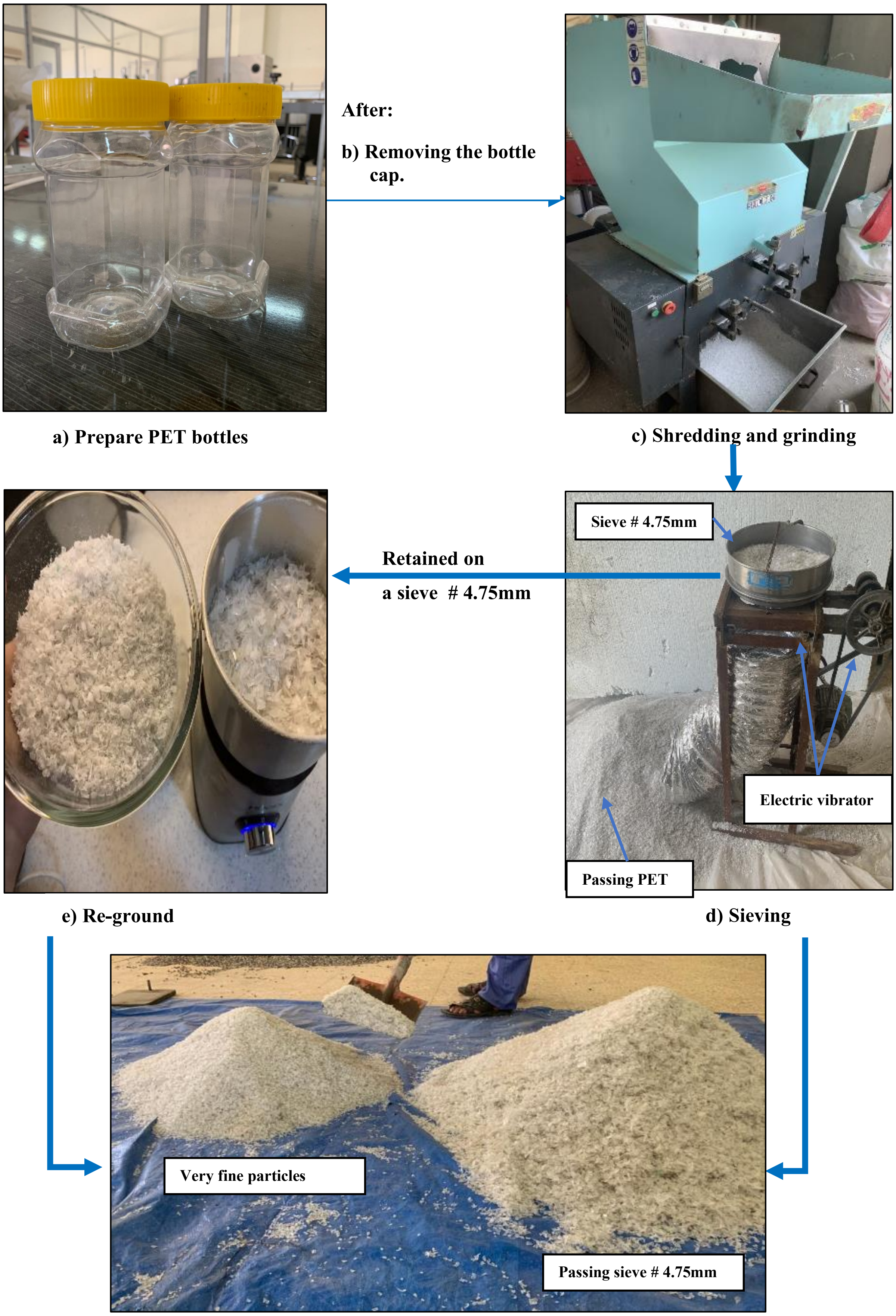
c) Shredding and grinding of bottles to smaller size similar to sand, by plastic granulator machine (SG-600F Model SML), as this machine used for plastic manufacturing by Light plastic factory.

d) Then, the obtained particles were separated through sieves, by passing them through the sieve size 4.75 mm.

e) Retained particles on a sieve of 4.75 mm were re-ground by a coffee mill (Modex brand) to obtain very fine particles asymptotic to the powder.

f) Then, the particles that passed through the sieve of 4.75 mm are re-mixed with the re-grinded particles (very fine) to obtain a mixture close to fine aggregate.

Figure 3.2: Types of aggregate: (a) coarse; (b) PET; and (c) fine.



f) Re-mixed

Figure 3.3: Process of preparation of plastic PET-aggregate.

3.2.5.2 Physical and Mechanical Properties of PET Aggregate

After preparing PET aggregate, it was evaluated in terms of grading by sieve analysis, as shown in Table (3.5). While the other physical and mechanical properties, as shown in Table (3.6), were provided by the Light plastic factory. It can be noted from Table (3.5) and Figure (3.4), the sieve analysis of PET aggregate does not comply with natural sand grading due to the plastic texture character and plastic particles types, which are typically flaky, angular, and irregular particle, while the fine natural aggregate is typically spherical and granular particles.

Table 3.5: Sieve analysis of PET and fine aggregate.

Sieve size (mm)	% Passed of fine aggregate	% Passed of waste PET particles
10	100	100
4.75	100	100
2.36	80	35
1.18	65	5
0.6	50	1
0.3	19	0
0.15	5	0

Table 3.6: Physical and mechanical properties of used PET *

Property	Results
Specific gravity	1.39
Water absorption (24 h)	Nil
Shape of particles	Flaky or flat particles
Bulk density	850 ± 10 kg/m^3
Thickness	0.35 mm
Color	Crystalline white
Tensile strength	79.3 MPa
Approx. melting temperature	230–250 °C
Tensile modulus	4.0 GPa

* These results are provided to us by the Light plastic factory [104], and according to the product data sheet (SABIC PET BC210) [105].

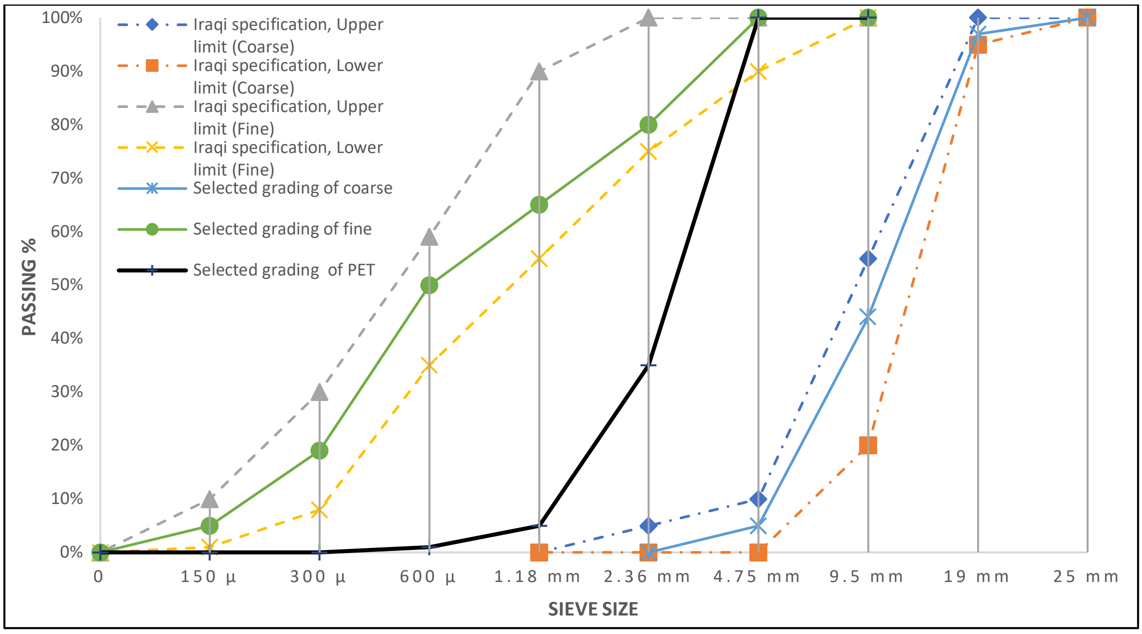


Figure 3.4: Sieves analysis of aggregates (fine, coarse, and PET).

3.2.6 Admixtures

A high range water-reducing admixture (superplasticizer), as shown in Figure (3.5), with a trade name (Sika ViscoCrete Hi-Tech 1316) [106] was added into the mixes to increase the workability. The manufacturer recommends that the dosage should in the range of (500–1500 g for 100 kg of the cement). In addition, this sort of admixture compatible with ASTM C494 (type D and G) [107], as cited in the product data-sheet [106]. Table (3.7) present the main properties of this superplasticizer.

Figure 3.5: Superplasticizer with a trade name (Sika ViscoCrete Hi-Tech 1316).

Table 3.7: Specification of superplasticizer *

Properties	Description
Appearance	Brownish liquid
Specific gravity	1.123 ± 0.01 kg/l
Chloride content	Max. 0.1% Chloride-free
Chemical Base	Modified polycarboxylates based polymer

* According to the product data sheet (Sika ViscoCrete Hi-Tech 1316) [106].

3.2.7 Carbon Fiber Reinforced Polymer (CFRP)

Unidirectional CFRP sheets (fabrics) (SikaWrap - 300C) [108] with fibers directed in one direction only (along the longitudinal axis) were used in this test program. The thickness of sheets for wrapping the plain standard cylinders was 0.167 mm. The CFRP sheet characteristics were based on the specifications of the supplier, Sika Company, as shown in Table (3.8) and Figure (3.6).

Table 3.8: Properties of CFRP Sheet *

Characteristics	Manufacturer data
Ultimate tensile strength (MPa)	4000
Modulus of Carbon Fiber (GPa)	230
Ultimate tensile elongation (%)	1.7
Thickness (mm)	0.167
Fiber density (g/cm^3)	1.82
Areal weight (g/m^2)	304 ± 10
Fiber orientation (°)	0
Fabric width (mm)	500

* According to the product data sheet (SikaWrap - 300C) [108].

Figure 3.6: CFRP sheets preparation.

3.2.8 Adhesive Epoxy

Epoxy resins are generally used to bond the CFRP on the concrete surface. The adhesive material (Sikadur-330) [109], as shown in Figure (3.7), was used in this experiment. The epoxy resin adhesive system consists of the main resin portion (Part A) (white color) and the hardener (Part B) (grey color), blended together at a particular volume ratio (4A:1B) for about 10 minutes until the color was grey. Then, applied on the concrete surface using a paintbrush. Table (3.9) lists the material characteristics of the epoxy adhesive provided by the manufacturer (Sika Company).

Figure 3.7: Adhesive Epoxy (Sikadur-330), Part (A and B).

Table 3.9: Material characteristics of epoxy adhesive*

Characteristics	Manufacturer data
Modulus of elasticity (MPa)	4500
Elongation limits (%)	0.9
Tensile strengths (MPa)	30
Mixing ratio (by weight)	Part (A) ¼ 4**:** Part (B) ¼ 1
Color (Mixed)	Light grey
Density (kg/l)	1.30 ± 0.1 (A + B mixed) (at + 23 °C)

* According to the product data sheet (Sikadur-330) [109].

3.2.9 Surface Repair of Specimens Bodies

The surface of the cylinders bodies, that containing only 50% of the plastic aggregate, was treated with a 2 mm thick voids filling material. The treatment was applied in two forms: (i) the full body of the cylinder, when used for wrapping; and (ii) a partial (strain gauge position) for the plain cylinders. The reason for this process is due to present a large number of voids on the surface of the specimens bodies in the form of honeycombs which would have hindered the work of the confinement and the test of the stress-strain curve. The properties of used material, shown in Table (3.10) and Figure (3.8), with a trade name (Sikadur-31) [110].

Table 3.10: Material characteristics of Sikadur-31*

Characteristics	**Manufacturer data**
Modulus of elasticity (MPa)	4300
Compressive strengths (MPa)	40-45 (Curing 1 day)
Tensile strengths (MPa)	15-20 (Curing 10 days)
Bond strength (MPa)	> 4 (Curing 10 days)
Mixing ratio (by weight)	Part (A) 4.5**:** Part (B) 1.5
Color (Mixed)	Grey
Density (Mixed) (kg/l)	1.65 (at + 20 °C)

* According to the product data sheet (Sikadur-31) [110].

Figure 3.8: Application of voids filling material (Sikadur-31): (a) Applying; (b) Full applying (before and after); and (c) Partial applying.

3.3 Preparation of Samples

3.3.1 Mix Proportion

In this experimental study, nine concrete mixes were produced containing different volumetric replacement of fine natural aggregate (0%, 25%, and 50%) by PET plastic waste aggregate with three different grades: M20, M30, and M40. The mix design was made according to the American method ACI 211.1-91-R-02) [111] as shown in Appendix (B), to achieve the required cylinders compressive strength by 28 days.

Moreover, in order to have a required slump (100 ± 10 mm) for reference mixes only, several trial mixtures have been done to pick an appropriate dose of high range water reducer admixture (superplasticizer). The details of the dosage of superplasticizer showed in Table (3.11). The resultant mix proportions of all the mixes by weight for one cubic meter volume of concrete are shown in Table (3.11).

On the other hand, for notation mentioned in Table (3.11), the naming of mixes followed the rules: (i) the first letter (R) followed by a numeral represents the replacement percentage of PET; and (ii) the second letter (WC) followed by a numeral (40/45/55) defines the w/c ratio. For instance, R50WC45 refers to a PET replacement ratio of 50% with w/c-ration of 0.45.

Table 3.11: Concrete mixture proportion

Components	**Content (kg/m^3)**								
	w/c = 0.40			**w/c = 0.45**			**w/c = 0.55**		
	0%	25%	50%	0%	25%	50%	0%	25%	50%
Notations:	R0WC40	R25WC40	R50WC40	R0WC45	R25WC45	R50WC45	R0WC55	R25WC55	R50WC55
Cement	460	460	460	387	387	387	320	320	320
Water	174	174	174	174	174	174	174	174	174
Gravel	955	955	955	955	955	955	955	955	955
Sand	861	645.7	430.5	880	660	440	940	705	470
PET**	0	110.8	221.6	0	113.2	226.5	0	120.9	241.9
SP**	4.14	4.14	4.14	3.29	3.29	3.29	2.81	2.81	2.81

* SP: superplasticizer;

** weight of SP determined as: =(% replacement * total wt. of sand * PET specific gravity) / sand specific gravity * 100).

3.3.2 Test Specimens

A total of 117 concrete cylinders and 54 concrete cubes with a dimension of, respectively, (150 × 300) mm, and (100 ×100) mm were prepared and tested. For each test, two or three nominally similar specimens were prepared and checked to ensure the reliability of the test results. These cylinders and cubes were divided into nine mixes in terms of the grade (w/c) and replacement ratio. Table (3.12) shows the number of specimens and the curing age applied for each test, corresponding to the substitution ratio and the w/c ratios.

Table 3.12: Details of test specimens.

Grade/ w/c	PET ratio %	Unconfined-specimens											Confined-specimens
		Fresh den.	**Slump**	**Dry den.**	**Water absorp.**	**Poros.**	**Compressive strength**			**Split ten.**	**UPV**	**Thermal Cond.**	**Com. Str.**
		Imm.	Imm.	28d	28 d	28 d	7 d	28 d	90 d	90 d	7, 28, and 90d	Theor.	90 d
M40 / 0.40	0	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	25	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	50	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
M30 / 0.45	0	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	25	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	50	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
M20 / 0.55	0	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	25	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.
	50	-	-	→	3 cu.	←	2 cy.	2 cy.	3 cy.	3 cy.	3 cu.	-	3 cy.

Immed.= Immediately; d= days; = cu=cube; cy= cylinder.

3.3.3 Mixing Process

Concrete mixing is necessary to achieve the required workability and homogeneous blends. The mixtures were prepared in the concrete laboratory at the University of Duhok. In order to monitor and standardize the same mixing process for all experiments, the processes for all concrete mixtures have been carried out in an electrical rotary tilting drum mixer of 0.1 m^3 capacity, as shown in Figure (3.9-a), and according to ASTM C192/C192M [112]. A constant amount of 0.035 m^3 of materials was prepared for each mixture. Besides, shovels and scoops were used to deposit concrete in the molds. The same methodology was used for the preparation of all mixtures.

The steps of mixing that were applied in this study were based on ASTM C192/C192M [112], as used in the previous studies, like [8], [70]. As follows:

i. The coarse aggregate was washed to eliminate any impurities and to achieve a saturated surface dry condition (SSD). Similarly, the fine aggregate was also wetted to achieve (SSD) condition. Before the mixer was operated, the ingredients were first hand-mixed in dry condition (fine aggregate + PET aggregate).

ii. The coarse aggregate and some water were introduced to the blender and turn on the mixer for half a minute.

iii. The fine aggregate and PET were added with the rest of the water while the mixer was rotating. Then, after about a minute,

iv. The cement material was added without stopping the mixer.

v. The solution (water + SP) was gradually added.

vi. Mixing the concrete after the mixer contains all the ingredients for (3-4) minutes, then a break for two minutes. During a break, the ingredients are manually mixed inside the mixer by a steel trowel and finally, running the mixer for about two additional minutes, to get a consistency in the texture of the concrete.

3.3.4 Casting

After the mixing process is finished, the mixture material is emptied and poured into the molds using the iron molds for that purpose. The molds are cleaned before casting, rigidly tightened, and lightly oiled to avoid their adherence to the concrete. After mixing, the materials are placed by filling cylinders, cubes in three layers, and compaction handily by Mallet hammer according to ASTM C192 [112]. A steel trowel had been used to smooth out the top surface of the concrete specimen. Then nylon sheets and a thick cloth used to cover specimens for 24 hr., as shown in Figure (3.9-b), to prevent water evaporation.

3.3.5 Curing

To achieve good concrete quality, curing is applied, in which, the method of curing controls the rate of humidity loss through the continuous moisturizing of the concrete. This is accomplished by creating an effective moisture condition. For this reason, after 24 hrs. from casting concrete, all the samples were put in a curing basin at around 25 °C. The curing status of the laboratory basin was based on ASTM C192 [112]. Figure (3.9-c) shows the samples in the curing basin.

(a) **(b)** **(c)**

Figure 3.9: Preparation of Specimens: (a) Mixing; (b) Casting and Covering; and (c) Curing

3.3.6 Capping

Capping the concrete cylinders is important to ensure that the load is uniformly distributed on the cylinder's surface during the compression test. For this purpose, before testing, as shown in Figure (3.10), all the plain concrete and CFRP-wrapped cylinders were capped using a 3 mm thick layer of the Sulfur capping compound. Capping the confined and unconfined cylinders followed the procedures prescribed by the ASTM C617 [113].

(a) (b)

(c)

Figure 3.10: Capping process: (a) Sulphur type; (b) heating and molding; and (c) samples after drying.

3.3.7 CFRP Wrapping Process

The CFRP wrapping process is shown in Figure (3.11). Prior to wrapping, the cylinders were dry and clean, and the concrete had a minimum strength of not less than 90 days. At the beginning of the wrapping process, the thin layer of dust covering the cylinders was removed with an air compressor. After that, CFRP sheets were cut into strips of the desired lengths and widths using a pair of scissors. Then, the epoxy coating was prepared by mixing the epoxy resin (part A and B) in the proportion described previously in section 3.2.8. After the cylinders are set upright, they are completely coated with an epoxy coat using a paintbrush. The next stage was to carefully wrap CFRP sheets around cylindrical specimens. The fibers are directed only to the hoop direction. Besides, a 120 to 125 mm overlap was provided to prevent slippage between CFRP layers. The location of the overlap for all specimens is shown in Figure (3.12). Also, the upper and lower ends of the confined specimens were further strengthened with roving carbon fiber with 50 mm width to prevent premature failures. Then, after 24 hr., the high strength Sulfur capping was applied to the top end of each specimen. Finally, the confined concrete specimens were treated in the laboratory for seven days. It should be noted that a similar practice (the above steps) has previously been used by [94], [114].

Figure 3.11: CFRP Wrapping Process: (a) cleaning; (b) cut of laminates; (c) mixing the epoxy resin; (d) coat the cylinders; (e) wrap CFRP laminates; (f) confinement the upper and lower ends; and (g) capping and curing .

3.3.8 Instrumentation

Fiber roving and uneven hardened epoxy need to be smoothed in order to fix the strain gauge on the cylinders. Sandpaper was used to smooth the fiber surface and then cleaned with the isopropyl alcohol. Then, strain gauges were installed evenly spaced at the mid-height of all specimens. As shown in Figure (3.12), for plain concrete, two strain gauges (model PL-60-11-3LJC-F) were mounted, one horizontally and one vertically as T-shaped. While for confined cylinders, four strain gauges (model BF350-3AA) were mounted, two horizontally and two vertically as T-shaped. The stress measurements were connected to the digital collector (data logger) for data collection during compression testing as shown in Figure (3.13).

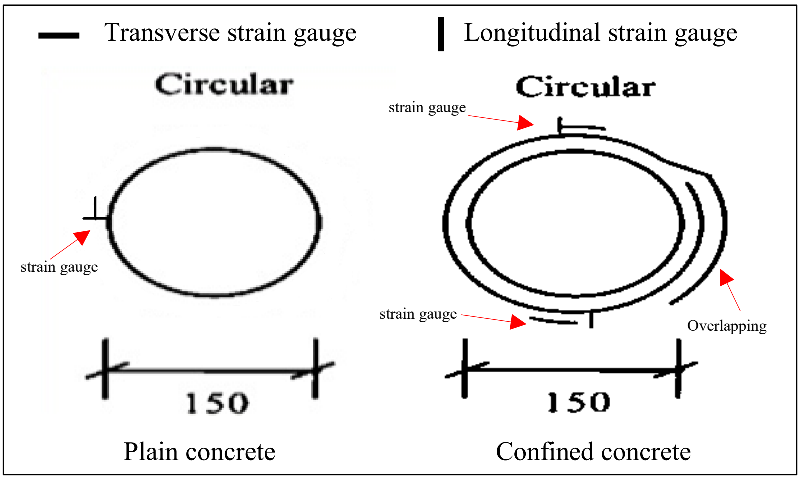


Figure 3.12: Details of cross-sectional dimensions, CFRP overlap positions, and location of strain gauges.

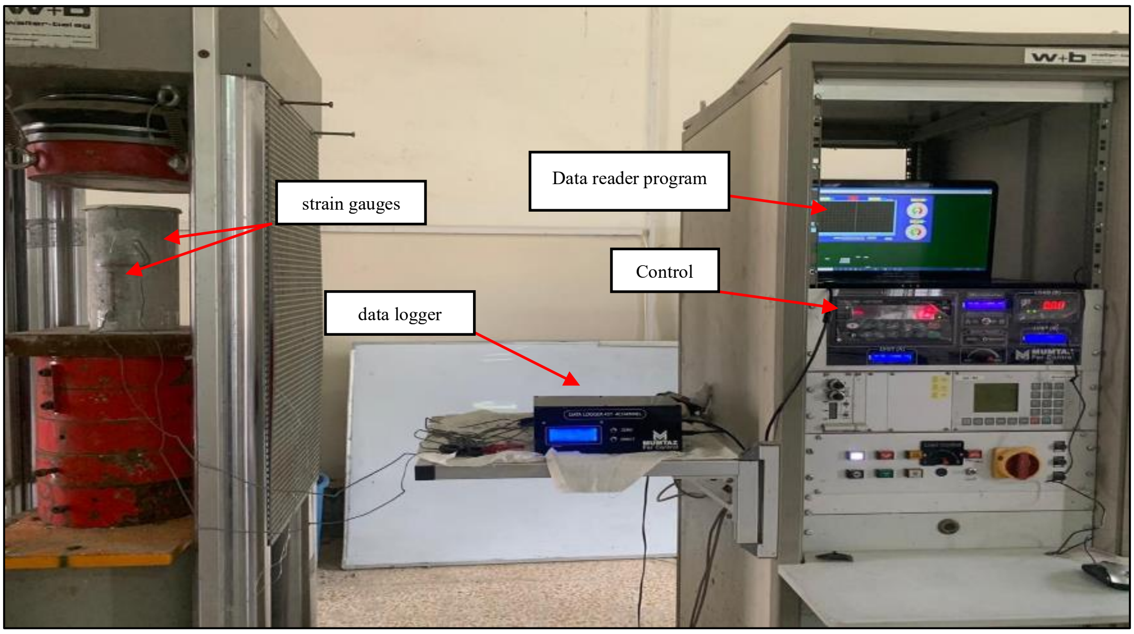


Figure 3.13: Compression test application with equipment's.

3.4 Equipment and Testing Procedure

3.4.1 Fresh Concrete Tests

3.4.1.1 Workability (Slump Test)

A slump test was carried out to determine the workability of both control concrete and PET in fresh condition and also to find out the impact of the various ratios of substitution on workability. The slump test was measured in accordance with ASTM C143 [115]. For every mixture in the experimental plan, a sample of fresh concrete was placed into a cone mold and compacted by a rod. The slump value is equivalent to the vertical distance between the original location and the moved site of the middle of the concrete top surface after the mold has been raised. As mentioned earlier in this study, only for each reference concrete mixtures of w/c (0.40, 0.45, and 0.55), the SP ratio was modified to have the workability (slump of 100 ± 10 mm). Therefore, several trial mixtures have been done to pick an appropriate dose of SP. Figure (3.14) shows some failed trial mixtures of slump, while Figure (3.15) shows results of some replacement ratios.

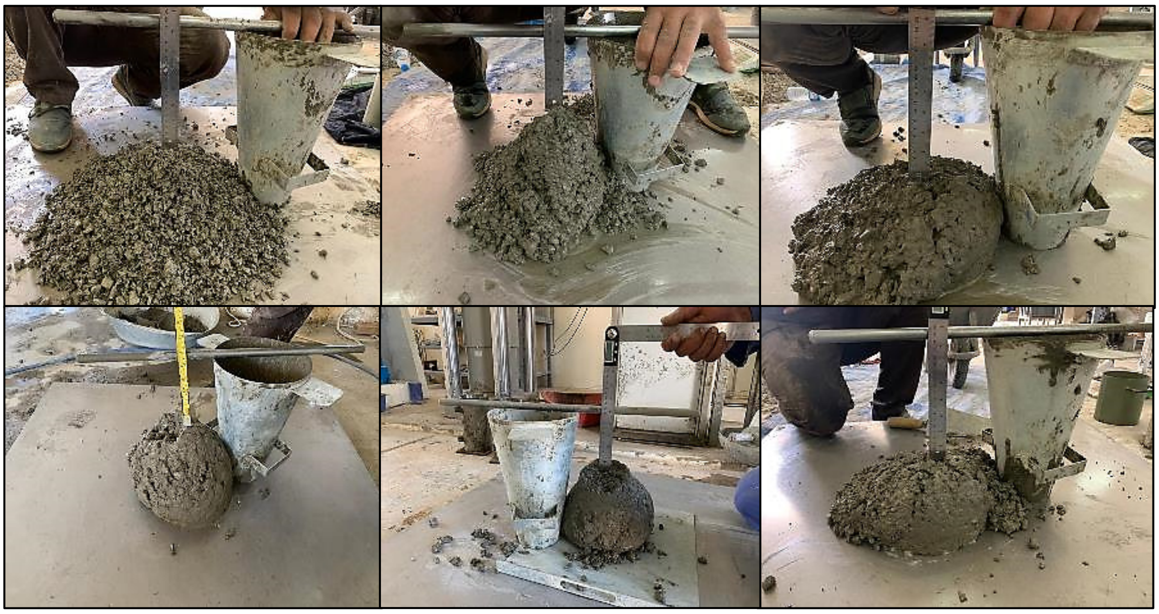


Figure 3.14: Some of failed trial mixtures (slump test), that conducted to choose the optimum dose of superplasticizer.

Figure 3.15: Slump test for replacement ratio of: (a) 0 % ; (b) 25 %; and (c) 50 %.

3.4.1.2 Fresh Density

As shown in Figure (3.16), the fresh density for all mixes was measured immediately after mixing, according to ASTM C138 [116]. It was calculated by the following equation:

$$Fresh\ density\ of\ concrete\ (kg/m^3) = (M_c - M_m)\ /\ V_m \quad \text{3-1}$$

Where:

M_c: mass of filled mold with concrete (kg);
M_m: mass of empty mold (kg); and
V_m: volume of the mold (m^3).

Figure 3.16: Fresh density test for replacement ratio of: (a) 0 % ; (b) 25 %; and (c) 50 %.

3.4.2 Hardened Concrete Tests

3.4.2.1 Dry Density

The dry density was determined according to ASTM C642 [117], as shown in Figure (3.17). The test was conducted at 28 days old by using cubic samples (100 mm). The test procedures for the samples included the following summary: calculation of (i) the dry mass after 24 hours in the oven, called (A); (ii) the saturated mass after immersion in water for 48 hours, called (B); (iii) the saturated mass after boiling with water for 5 hours, called (C); and (iv) finally, the mass is in the water, called (D). Moreover, the following equation was used to calculate dry density:

$$\text{Dry density } (\mathrm{kg/m^3}) = [A/(C-D)]\, p_w \qquad \text{3-2}$$

where
A: oven-dried weight of specimen, (kg)
C: mass of surface dry sample in air after immersion and boiling, (kg)
D: mass of sample in water after immersion and boiling, (kg)
$\rho_{w:}$ density of water, (kg/m^3)

Figure 3.17: Dry Density calculation: (a) dry mass; (b) saturated mass after immersion; (c) saturated mass after boiling; and (d) mass is in the water

3.4.2.2 Water Absorption

The water absorption test was performed according to ASTM C642 [117], as shown in Figure (3.17). The test was carried out on 28-day-old cubic samples (100 mm). As for the procedures followed, it is the same as those mentioned previously in the dry density test. Besides, the following equation was used:

$$Water\ absorption\ \% = [(B - A)\ /\ A]100 \tag{3-3}$$

where:
A: the mass of the dried sample (kg).
B: the dry mass in the air after immersion, (kg).

3.4.2.3 Voids

Also, the ASTM C642 [117] test method, encompassed the calculation of the percentage of voids in hardened concrete. The test was conducted at 28 days old by using cubic samples (100 mm). As for the procedures followed, also, it is the same as those mentioned previously in the dry density test. Besides, the following equation was used:

$$Voids\ (\%) = \ [(C - A)/(C - D)]\ 100 \tag{3-4}$$

where
A: oven-dried weight of specimen, (kg)
C: mass of surface dry sample in air after immersion and boiling, (kg)
D: mass of sample in water after immersion and boiling, (kg)

3.4.2.4 Compressive Strength

The compressive strength test was performed on concrete cylinder specimens of 150 mm diameter and 300 mm high, according to ASTM C39 [118]. As illustrated in Figure (3-18), the compression tests were carried out with a universal test machine (walter+bai ag) with a capacity of 3000 kN, and a loading rate of 0.33 MPa/sec. Tests were conducted at ages 7, 28, and 90 days. Besides, the following equation was used:

$$f_c' = \frac{P}{A} \quad \text{3-5}$$

where:

f_c': concrete compressive strength, (MPa)

A: cross-section area of specimens, (mm^2)

P: maximum load on failure, (N)

Figure 3.18: Compression testing machine.

3.4.2.5 Splitting Tensile Strength

The splitting tensile strength test, as shown in Figure (3.19), was performed on concrete cylinder specimens of 150 mm diameter and 300 mm high; according to ASTM C496 [119]. The load was continuously applied at a rate of 1.2 MPa/min to failure. Besides, the following equation was used:

$$f_t = \frac{2P}{\pi l d} \quad \text{3-6}$$

where:

f_t: splitting tensile strength, (MPa)

P: maximum applied load, (N)

l: cylinder Length, (mm)

d: cylinder diameter, (mm)

Figure 3.19: Splitting tensile strength test.

3.4.2.6 Stress-Strain Curve

The stress-strain curves of the plain and confined concrete cylinders were carefully investigated during the compression tests at 90 days only. For each load increment, the corresponding axial and lateral strains were recorded (see Figure (3.20).

	A	B	C	D	E	F	G	H	I	J
1			Load (Kn)			Axial 1 (ms)	Lateral 1 (nm)	Axial 2 (ms)	Lateral 2 (nm)	
2	7:26:46 PM	03-Nov-20	12.6	0	0	-68	18	-155	15	
3	7:26:47 PM	03-Nov-20	13.2	0	0	-84	22	-197	19	
4	7:26:48 PM	03-Nov-20	14.2	0	0	-104	23	-236	22	
5	7:26:49 PM	03-Nov-20	14.6	0	0	-124	25	-278	25	
6	7:26:50 PM	03-Nov-20	15.4	0	0	-149	28	-324	29	
7	7:26:51 PM	03-Nov-20	16.2	0	0	-174	30	-370	33	
8	7:26:52 PM	03-Nov-20	17.2	0	0	-202	35	-415	37	
9	7:26:53 PM	03-Nov-20	18	0	0	-232	37	-460	39	
10	7:26:54 PM	03-Nov-20	19	0	0	-264	44	-507	44	
11	7:26:55 PM	03-Nov-20	19.8	0	0	-297	45	-552	48	
12	7:26:56 PM	03-Nov-20	20.8	0	0	-333	52	-596	52	
13	7:26:57 PM	03-Nov-20	21.6	0	0	-369	54	-647	55	
14	7:26:58 PM	03-Nov-20	22.4	0	0	-398	59	-686	58	
15	7:26:59 PM	03-Nov-20	23.2	0	0	-436	65	-732	63	
16	7:27:00 PM	03-Nov-20	24.2	0	0	-476	70	-780	67	
17	7:27:01 PM	03-Nov-20	25.2	0	0	-517	76	-824	70	
18	7:27:02 PM	03-Nov-20	26.2	0	0	-562	81	-874	74	
19	7:27:03 PM	03-Nov-20	27.2	0	0	-605	86	-923	77	
20	7:27:04 PM	03-Nov-20	28.4	0	0	-649	92	-971	82	
21	7:27:05 PM	03-Nov-20	29.6	0	0	-704	101	-1034	87	
22	7:27:06 PM	03-Nov-20	30.4	0	0	-741	104	-1080	91	
23	7:27:07 PM	03-Nov-20	31.4	0	0	-782	112	-1135	95	

Figure 3.20: Stress-strain measurements.

3.4.2.7 Ultrasonic Pulse Velocity (UPV)

UPV test, as shown in Figure (3.21), was performed on concrete cubes specimens according to ASTM C597 [120]. A transducer with a vibration frequency of 52 kHz was also utilized. In addition, the grease jelly was placed between the test surfaces of the contact faces of the transducers and specimens to assure well connection. Also, the device setting is frequently checked by using the reference bar. Besides, the following equation was used:

$$V = L/T \tag{3-7}$$

where:

V: UPV (Km/sec)

L: displacement between the center of transducer face (mm)

T: transit time (microsecond)

Figure 3.21: Ultrasonic Pulse Velocity test.

3.4.2.8 Theoretical Thermal Conductivity

Knowledge of the thermal conductivity behavior of building materials is essential for assessing heat transfer rates. Thermal conductivity (k_c) can be described as the heat energy transmitted through a unit length of the material when there is a temperature gradient of one unit [121]. k_c is determined in Watts per meter-Kelvin (W/mK). In this study, the test of thermal conductivity is carried theoretically according to the exponential equation provided by [122], which connects the dry density to the coefficient of thermal conductivity. Also, the coefficient of thermal conductivity depending on the type of aggregate utilized in concrete mixes. [122] equation as follows:

$$k_c = 0.072e^{0.00125d} \qquad 3\text{-}8$$

where

k_c = the coefficient of thermal conductivity for concrete (W/mK)

d = oven-dry density (kg/m^3)

CHAPTER 4
RESULTS AND DISCUSSION

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4.1 Introduction

This chapter presents the results of the test program designed, as described in chapter three. The test results of this study are divided into three sections; the first section focuses on the behavior of recycled PET aggregate in concrete mixes; the second section focuses on how concrete that contains PET behaves with CFRP sheet wrapping; while the third section presents the relationship between different PET-concrete properties.

4.2 Behavior of Concrete Containing PET Plastic Aggregate

4.2.1 Workability (Slump Test)

In this study, the slump test was considered as the primary measure of concrete workability. Figure (4.1) shows the slump results of concrete mixes with different PET and w/c ratios. It can be noted that the slump reduces as the content of PET increases regardless of the w/c ratio. For example, compared to the reference mix, at the 25% replacement, the reduction rate is 33.33% (w/c of 0.40), 38.1% (w/c of 0.45), and 41.28% (w/c of 0.55). While, at 50% replacement, the reduction rate is 79.9% (w/c of 0.40), 82.86% (w/c of 0.45), and 90.83% (w/c of 0.55). However, the mixes used were still workable to some extent. The reason for this decrease is attributed to PET particles have a larger surface area than natural sand because of their irregular and flat shape. As a result, there would be more friction between the particles, which would lead to less workability in the mixtures. These observations have already been verified by several authors, as it was stated previously in chapter two, section 2.2.3.1, and clearly illustrated in Figure (2.2), by [8, 15, 17, 37, 51, 53-56].

Moreover, with the increase of PET content, the fluidity and consistency of fresh concrete are reduced. This influence is more significant when the ratio of w/c increases, as a result of bleeding, since the interface between PET particles and the hydrated Portland cement present more porous when increasing the w/c ratio because the excess water does not react with the cement. This behavior occurred as a result of the inability to water absorption and flat form of the PET particles. Thus, lowering the workability of the mixture. This behavior was praised by [8, 15, 27, 52].

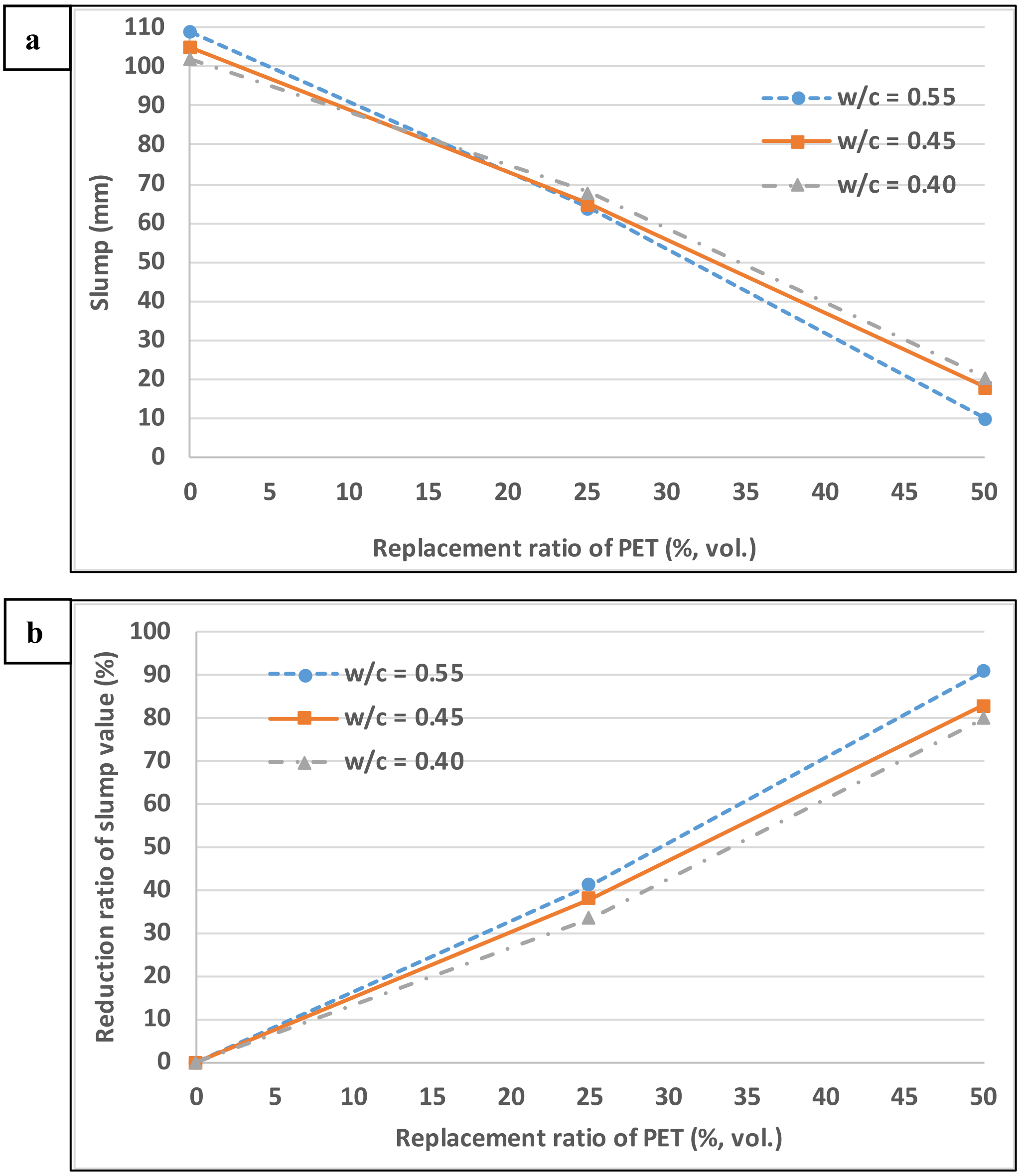

Figure 4.1: Slump test results for different ratios of PET and w/c: (a) slump value; and (b) reduction ratio.

4.2.2 Fresh and Dry Densities

Figures (4.2) and (4.3) show the fresh and dry densities results with different proportions of PET particles and w/c ratios. The results show that the fresh and dry densities of all mixtures decrease as the content of plastic aggregates increases. For fresh density, the maximum loss is equal to 17.75% for concrete with a ratio of 0.55 w/c and a 50% replacement rate. While for dry density, the maximum loss is equal to 21.63% also for concrete with a ratio of 0.55 w/c and a 50% replacement rate. The reason for this reduction is due to lower PET particle density compared to natural sand, leading to a decrease in concrete density. These observations have already been verified by several authors, as it was stated previously in chapter two, section 2.2.3.2, and clearly illustrated in Figure (2.3), by [8, 17, 37, 40, 50, 53, 55-58, 60, 74].

On the other hand, the decline in concrete density is more pronounced if the w/c ratio is increased, especially for dry density, as shown in Figures (4.2-b) and (4.3-b). This has been related to the excess water in the concrete specimens that do not take part in the water and cement reaction, so small canals are formed that can form pores after drying. Therefore, lower unit weights are achieved for higher water to cement ratios, as confirmed by [49], [67].

Moreover, values of dry density for mixes containing 0% of PET plastic aggregates decrease from 2388 kg/m^3 (w/c of 0.40), 2376 kg/m^3 (w/c of 0.45), and 2347 kg/m^3 (w/c of 0.55) to 1993 kg/m^3, 1964 kg/m^3, and 1839 kg/m^3, respectively, for mixes containing 50% of PET plastic aggregates. Thus, the all dry density values, at the replacement ratio of 50%, were lower than 2000 kg/m^3 (Minimum dry density needed for lightweight structural concrete according to classification of RILEM-LC2 [59]. Accordingly, these concretes are classified as lightweight structural concrete. This result is also within the scope of the results obtained by Azhdarpour, et al. [68].

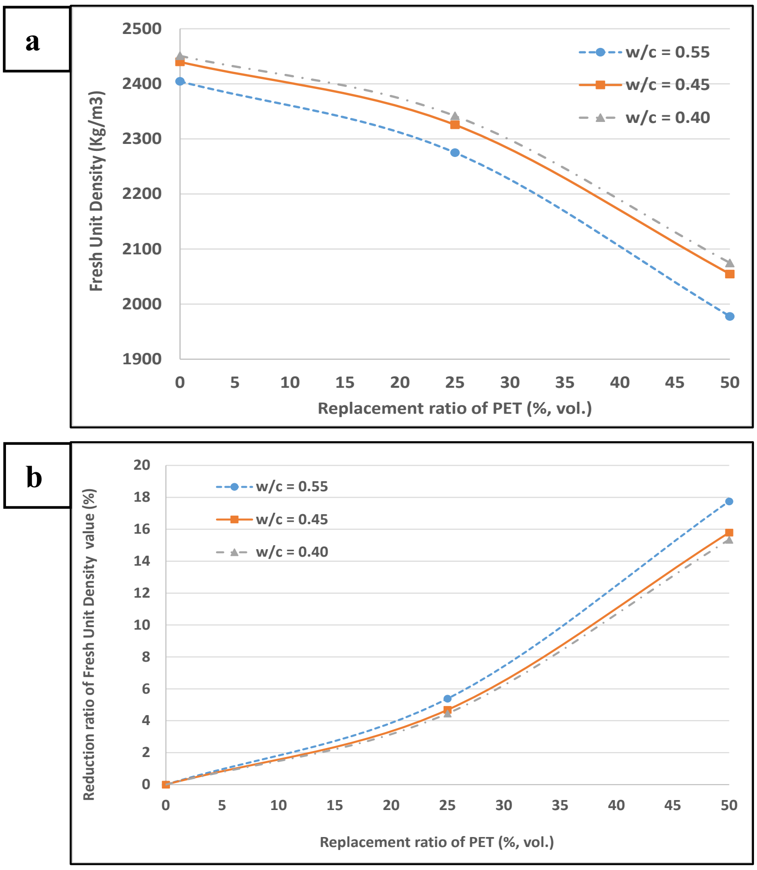

Figure 4.2: Fresh density test results for different ratios of PET and w/c: (a) fresh density value; and (b) reduction ratio.

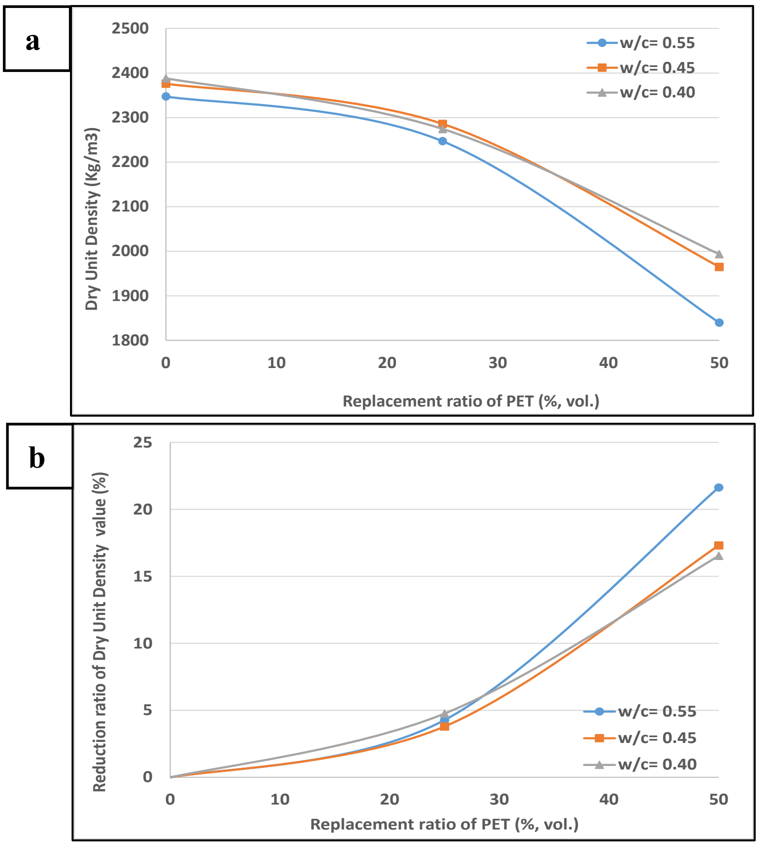

Figure 4.3: Dry density test results for different ratios of PET and w/c: (a) dry density value; and (b) reduction ratio.

4.2.3 Water Absorption and Porosity

Water absorption refers to the degree of material porosity by measuring the percentages of water absorbed under a particular condition [12], [123]. Figures (4.4) and (4.5) show the absorption of water and the porosity of concrete in accordance with the amount of PET aggregate replacement and the w/c ratios. Each value shown is an average of three measurements. From the data presented, the water absorption and porosity of concrete, regardless of the w/c ratio, increases significantly by increasing the PET amount in the mixture. For example, compared to the reference mix, at the 50% replacement, the increased rate of water absorption and porosity was, respectively, 101.25% and 69.32% (w/c of 0.40), 143.6% and 89.96% (w/c of 0.45), and 181% and 95.85% (w/c of 0.55). This behavior occurred because of the fact that natural aggregates and plastic are not sufficiently combined in the concrete matrix, leading to a porous matrix. This could be attributed to two factors: (i) the smooth surface and irregular shape of most plastic aggregates weakens the bond between the aggregates and cement matrix; and (ii) plastic aggregates almost have no absorption capacity for water, this will cause water to accumulate in the ITZ. As a consequence, after these samples have dried, created blank cavities. Accordingly, allowing the water absorption to increase when the specimens are exposed to water. This observation was already verified by several authors, like [15], [52], [58], [71].

From the data presented in Figures (4.4) and (4.5), one can see that the water absorption and porosity increase when the w/c ratio increase. This attributed to, the coated surface of the aggregates is smaller in the case of a higher ratio of w/c. So, as the volume of paste is decreased, the pores in the concrete increase, and the water absorption increases. Moreover, as this study mentioned before, the surplus water in the concrete specimens that have not reacted to the cement and have not been absorbed by the waste PET particles, creates cavities after drying. Therefore, higher water absorption and porosity are achieved for higher water to cement ratios, as confirmed by [15], [24].

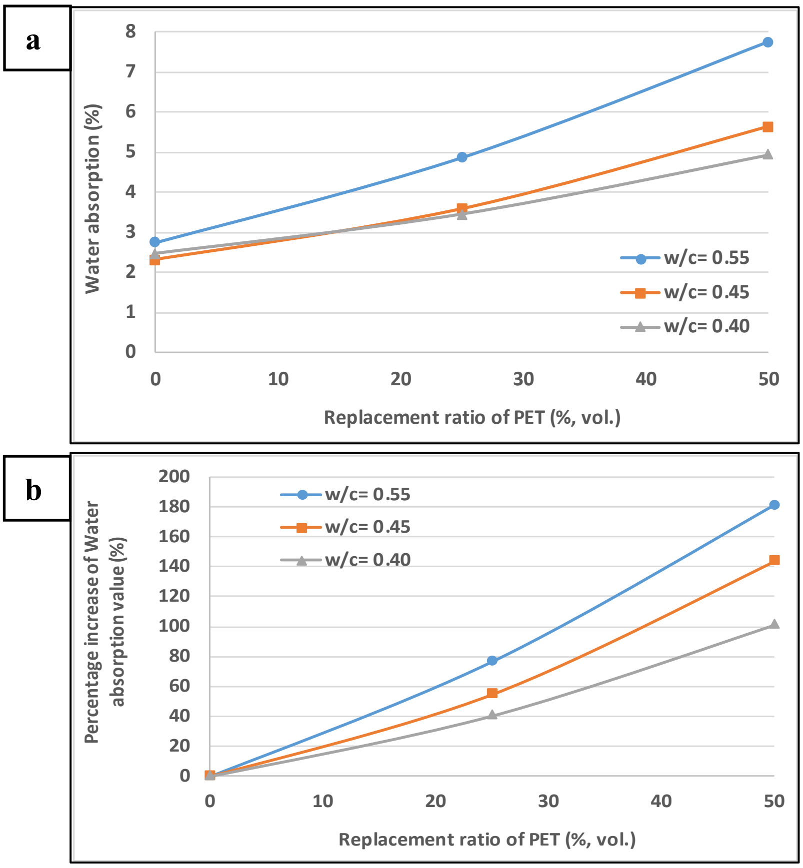

Figure 4.4: Water absorption test results for different ratios of PET and w/c: (a) Water absorption value; and (b) increase percentage.

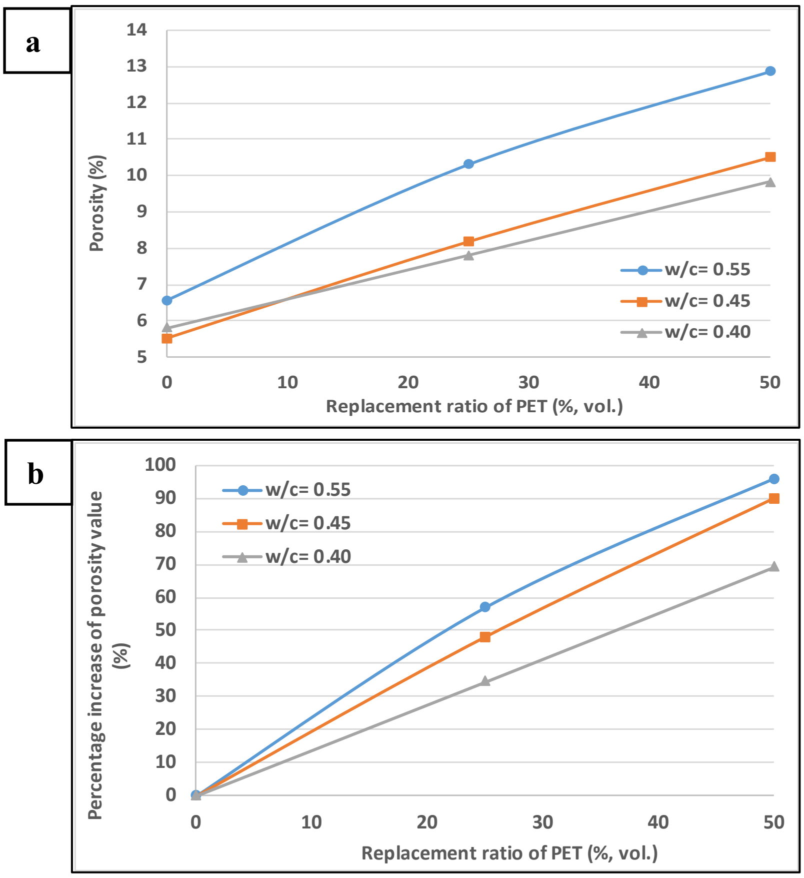

Figure 4.5: Porosity test results for different ratios of PET and w/c: (a) Porosity value; and (b) increase percentage.

4.2.4 Compressive Strength

To understand the impact of replacing a natural aggregate with a plastic aggregate with various w/c ratios on the compressive strength behavior of concrete at 7, 28, and 90 days, the experimental results are presented in Table (4.1). The presented results are the average of three specimens whose individual values are (±2.0) MPa relevant to the average mentioned in Table (4.1). Generally, and at all test ages, while the substitution rate of PET particles increases, the trend of compressive strength is further reduced. For example, compared to the reference mix, at the 25% replacement (90-days), the reduction rate in strength was 43.46% (w/c of 0.40), 40.96% (w/c of 0.45) and 25.2% (w/c of 0.55). While, at the 50% replacement, the reduction rate was 76.12% (w/c of 0.40), 76.82% (w/c of 0.45), and 74.41% (w/c of 0.55). This strength reduction can be labelled by the following reasons:

i. As a result of the smooth surface and flat shape of the plastic particles, the adhesive strength between the cement paste and the plastic waste surfaces is weakened. In which these plastic particles act as a barrier and prevent cement paste from adhesing to the natural aggregate. Thus, for concrete containing PET aggregates, the ITZ is weaker than in the control concrete; this decreases the resultant compressive strength.
ii. Furthermore, the water that had not been absorbed by the PET and that did not take part in the reaction of water and cement surrounded these aggregates leading to poorer bonds and makes small channels that, after drying, can form pores.

These observations have already been verified by several authors, as it was stated previously in chapter two, section 2.2.3.3, and clearly illustrated in Figure (2.4), by [8, 15, 17, 37, 40, 49-53, 55-58, 60, 62, 64-70, 74].

On the other hand, it is observed that when increasing the ratio of w/c, the compressive strength decreases, similar to the conventional concrete mixtures. Because, in the case of higher ratios of w/c, the coated surface of the aggregates is smaller, and as a result of lower paste volume, higher bleeding water content occurs. The latter (excess water), which is mainly located around PET particles, which do not participate in the reaction of water and cement, generates a weaker bond between the cement paste and the PET particles, also, generates some small channels which can form pores after drying, causing a decrease in strength. A similar trend was also reported by [8], [15],[27], [49], [67].

Table 4.1: Results of Compressive strength and Splitting tensile strength tests.

G*/ w/c	Symbols	Compressive strength (MPa)								Splitting tensile strength (MPa)	
		7 d	Variation (%)	SD	28 d	Variation (%)	SD	90 d	Variation (%)	90 d	Variation (%)
M40/ 0.40	R0WC40	64.14	-	2.40	77.08	-	2.91	80.13	-	6.07	-
	R25WC40	38.28	-40.31	2.97	44.48	-42.29	3.08	45.31	-43.46	4.23	-30.22
	R50WC40	17.14	-73.27	2.69	18.86	-75.53	3.01	19.14	-76.12	2.48	-59.11
M30/ 0.45	R0WC45	51.51	-	2.62	64.09	-	3.11	66.83	-	5.41	-
	R25WC45	32.16	-37.57	2.33	38.62	-39.74	3.18	39.46	-40.96	3.88	-28.20
	R50WC45	12.90	-74.96	2.90	15.26	-76.19	3.04	15.49	-76.82	2.18	-59.68
M20/ 0.55	R0WC55	34.26	-	2.12	44.48	-	2.90	47.73	-	4.38	-
	R25WC55	27.81	-18.83	2.47	34.79	-21.78	3.11	35.70	-25.20	3.49	-20.23
	R50WC55	10.03	-70.71	2.26	11.98	-73.07	2.83	12.21	-74.41	1.89	-56.87

* G: grade of concrete; SD: Standard Deviation.

4.2.5 Splitting Tensile Strength

To understand the impact of replacing a natural aggregate with a plastic aggregate with various w/c ratios on the behavior of splitting tensile strength of concrete at 90-days, the experimental results are presented in Table (4.1). Generally, the results show performance reductions of tensile strength for any pattern of substitution, like compressive strength but with less severe due to the flexible nature of plastic. Accordingly, decreases in split tensile strength can be attributed to the same reasons as decreases in compressive strength. These observations have already been verified by several authors, as it was stated previously in chapter two, section 2.2.3.4, and clearly illustrated in Figure (2.5), by [8, 15, 27, 38, 49-52, 55, 56, 62-64, 67, 68, 70].

4.2.5.1 Splitting Tensile Test Failure Modes

From the failure patterns for both PET-containing and non-containing concrete that shown in Figure (4.6), the splitting failures of plastic aggregate concrete specimens did not show the typical brittle failure that was noted in the reference concrete case. In other words, the incorporation of plastic waste aggregates in concrete changed the concrete specimen fracture mode from brittle to more ductile failure. It was also noted that the concrete control specimens had a sudden breakage accompanied by sound. In contrast, the failure occurred smoothly without sound during breaking for specimens with plastic aggregates. This behavior is possibly because of (i) according to Azhdarpour, et al. (2016) [69], the existence of flexible plastic particles at failure starting points. In this location (at the surfaces of failure), a part of the shear stress is transformed into tensile stress to overcome the tensile strength of the plastic waste. Also, plastic particles withstand part of the stress applied before being isolated from other materials. In other words, the angular and flat form of the plastic aggregate can serve as a bridge between the two split parts. In contrast, fine aggregates are semi-spherical and brittle, causing them to separate from the surrounding cement before failure. These observations agreed with those of [23, 38, 68]; and (ii) in specimens without plastic waste, a failure occurs in the matrix around the aggregates and through coarse aggregate in the ITZ. Whereas in PET-concrete, failure mainly occurs around PET particles because of the elastic modulus mismatch and, also, poor bond strength between cement paste and PET plastic waste aggregate. This remark is compatible with the observation of Kou, et al. [62]. Besides, as seen in Figure (4.6-c), the pores and cavities have appeared on the specimens external surface in honeycomb form. These observations are in line with those of Albano, et al. [15].

Figure 4.6: Failure modes with different PET replacement ratio: (a) 0%; (b) 25%; and (c) 50%.

4.2.6 Stress-Strain Behavior

The stress-strain curves determined from compression tests, with different percentages of PET content and w/c, are plotted in Figure (4.7). Noting that some of the plotted results may not correspond to the maximum compressive strength because the foil gauges were broken off before the sample reached failure. From the data presented, for a constant w/c ratio, it can be noticed that: (i) PET-concrete achieved the highest strain increase; and (ii) the peak compressive stress is less at a high plastic aggregate level, but the corresponding strains are higher. In other words, due to the high flexibility of plastic, the ductility behavior will be enhanced at high plastic aggregate substitutions. But, compared to the reference concrete, the peak compressive stress was lower. Consequently, these reductions impact the stress-strain graph and lead to a decrease in the gradient of the graph during its linear elastic phase. These observations agreed with those of [27], [65].

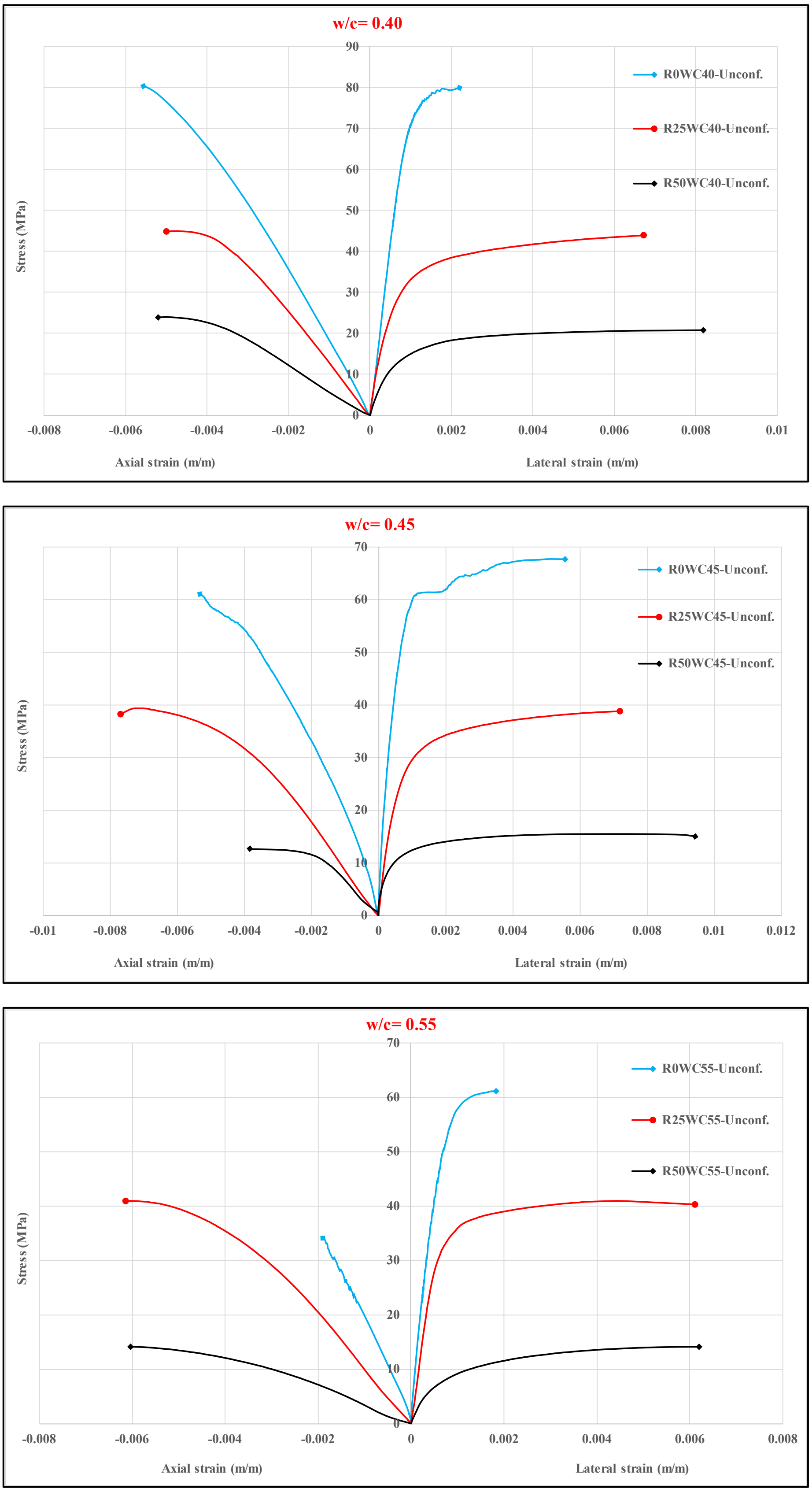

Figure 4.7: Stress-strain curve for unconfined cylinders with different ratio of PET and w/c.

4.2.7 Ultrasonic Pulse Velocity (UPV)

An ultrasonic pulse velocity (UPV) is a non-destructive test to verify concrete uniformity and quality. Durability and concrete strength are evaluated via the concrete specimen by determining the speed of an ultrasonic pulse. Mostly, pulse velocity is influenced by the moisture content, density, and elasticity of the material [73]. Table (4.2) presents the UPV performance at different curing ages (7, 28, 90) for concrete specimens with different PET content and w/c ratios. Each value shown is an average of three cubes. Results indicate that UPV decreases by increasing the PET content in the mixture. Such behavior can be attributed to: (i) the incorporation of PET directly affects the porosity of the concrete (cavities are formed), which in turn attenuates the velocity of the ultrasonic waves: and (ii) plastic particles have a plate structure (flat and angular shape), which has a role in becoming the refractive limit of ultrasonic waves. In contrast, as shown in Table (4.2), it can be observed that the UPV increased with curing age due to improving the chemical and physical properties of concrete as a result of continuing the hydration reactions. These observations were already verified by several authors, like [8, 15, 73, 74].

On the other hand, one can recognize from Table (4.2), that the UPV declines as the w/c ratio increases. This is attributable to extra water stored in the pores which leave empty holes in the concrete upon hardening. Such outcomes have already been confirmed by [8, 15].

Table 4.2: Ultrasonic pulse velocity test results.

G*/ w/c	Symbols	UPV (Km/s)		
		7 d	28 d	90 d
M40 / 0.40	R0WC40	5.05	5.20	5.24
	R25WC40	3.98	4.16	4.23
	R50WC40	3.33	3.53	3.62
M30/ 0.45	R0WC45	4.71	4.88	4.93
	R25WC45	3.82	3.97	4.03
	R50WC45	3.19	3.37	3.45
M20 / 0.55	R0WC55	4.29	4.48	4.55
	R25WC55	3.63	3.75	3.79
	R50WC55	3.08	3.23	3.28

4.2.8 Theoretical Thermal Conductivity

To increase understanding of the impact of the substitute of normal fine aggregate with a plastic aggregate with various w/c ratios on the thermal conductivity (k_c) behavior of concrete, the theoretical results obtained by the exponential equation provided by [122] are presented in Table (4.3). Moreover, as this study mentioned earlier, the coefficient of thermal conductivity of this equation depends on the type of aggregate utilized in the mixtures of concrete. From the data presented, it can be seen that with an increase in the content of PET aggregates, at a constant ratio of w/c, a significant decrease in thermal conductivity occurs. The reason for this decrease is attributed to (i) the PET aggregate had lower thermal conductivity (0.15-0.24 W/mK), compared with natural aggregate (2 W/mK), as stated by [75]. Therefore, the PET aggregates act to slow thermal heat spread, causing a decrease in thermal conductivity; and (ii) the presence of a large number of pores in the structure of PET-concrete, which reduces the thermal conductivity as a result of the low thermal conductivity of the air in these voids [73]. These observations were already verified by several authors, like [64, 73, 75-80]

On the other hand, from the data presented in Table (4.3), one can notice that the maximum reduction in thermal conductivity value is 46.99% (k_c = 0.71 W/mK) for 50% replacement of PET (w/c ratio of 0.55), in comparison with reference concrete (k_c = 1.35 W/mK). Consequently, these composites (50% PET with 0.55 w/c) could be utilized as a bearing insulator according to RILEM-LC2 [59] (k_c sample < 0.75 W/mK, and f_c' > 3.5 MPa). The results obtained are consistent with previous studies by[76], [77], [81].

Furthermore, depending on the results of this study along with the summary of previous studies, this study confirms some author's conclusions which indicated: (i) recycled PET plastic aggregate can be used in buildings for thermal insulation [78], [79], [80]; and (ii) concrete with a high PET plastic waste aggregate content (e.g., 50%) can be used in structurally insulation lightweight concrete components like a filler material for concrete masonry unit cavities [79].

Table 4.3: Thermal conductivity test results.

Grade / w/c	PET (%)	Dry Density (kg/m^3)	Theoretical Thermal Conductivity(W/mK)	
		28 days	Ref. ACI-122R [122]	
			$k_c = 0.072e^{0.00125d}$	Variation (%)
M40 / 0.40	0	2388.19	1.424	-
	25	2274.49	1.236	-13.25
	50	1993.40	0.867	-38.95
M30 / 0.45	0	2376.14	1.403	-
	25	2285.93	1.253	-10.66
	50	1964.92	0.839	-40.19
M20 / 0.55	0	2347.49	1.354	-
	25	2247.09	1.194	-11.79
	50	1839.77	0.717	-46.99

k_c = the coefficient of thermal conductivity for concrete (W/mK);

d = oven-dry density (kg/m^3)

4.3 Behavior of Concrete Containing PET Aggregates Confined with CFRP Fabrics

4.3.1 General

The key test results at 90 days of curing of all 54 confined and unconfined specimens (cylinders with dimensions 150 × 300 mm) are listed in Table (4.4). The compressive strength shown in the table represents an average of three specimens per mixture, while the results of the axial and lateral strains represent the mean of two specimens per mixture.

Table 4.4: Tests results (compressive strength, axial, and lateral strain) of confined and unconfined cylinders.

Grade / w/c	PET ratio %	Specimens symbols	CFRP layers	Compressive strength (MPa)		**Max. Axial strain (%)	**Max. Lateral strain (%)
				90 days	Variation of strength (%)		
M40 / 0.40	0	R0WC40*	0	80.13	-	-0.0056	0.0022
			1	86.81	+8.33	-0.011	0.0057
	25	R25WC40	0	45.31	-	-0.005	0.0067
			1	71.98	+58.86	-0.010	0.021
	50	R50WC40	0	19.14	-	-0.0052	0.0082
			1	40.81	+133.25	-0.014	0.012
M30 / 0.45	0	R0WC45	0	66.83	-	-0.0053	0.0051
			1	82.10	+22.84	-0.0042	0.014
	25	R25WC45	0	39.46	-	-0.0071	0.0072
			1	65.67	+66.42	-0.017	0.013
	50	R50WC45	0	15.49	-	-0.0038	0.0094
			1	34.09	120.02	-0.0050	0.0062
M20 / 0.55	0	R0WC55	0	47.73	-	-0.0019	0.0018
			1	69.97	+46.61	-0.0040	0.0109
	25	R25WC55	0	35.70	-	-0.0060	0.0044
			1	67.04	+87.79	-0.0074	0.014
	50	R50WC55	0	12.21	-	-0.0060	0.0062
			1	35.45	+190.27	-0.01325	0.0132

* R0WC40**:** The number following the letter R indicates the percentage of PET substitution; the number following the letters WC indicates the w/c ratio.

** Some of the results presented in this column do not correspond to the maximum compressive strength because the foil gauges were removed (broken off) before the sample reached failure. Therefore, these results, if they do not correspond to the maximum strength, then they represent the maximum value in the plotted curves.

4.3.2 Stress-Strain Behavior

The stress-strain curves of the nine mixes of specimens are shown in Figures (4.9) and (4.10), where the lateral strain values are shown on the right and the axial strain values are shown on the left.

Before describing the stress-strain behavior, some points can be illuminated, as follows: (i) the behavior of stress-strain curves will be described according to Figure (4.8), in which the three main portions are shown (the first part, the transition zone (TZ), and the second part); (ii) Figure (4.9) shows the regrouped stress-strain curves for confined samples only, since samples with the same w/c are shown together to analyze the influence of the PET substitution ratio. Besides, only one representative of the stress-strain curve is taken from each mix for a clearer visual effect; (iii) Figure (4.10) shows the regrouped stress-strain curves of confined and unconfined samples, to study the impact of the confinement. Also, only one representative stress-strain curve is taken from each mix; and (iv) in some cases, all-data points do not show in plotted curves (the behavior is uncompleted to the end), because the foil gauges were removed (broken off) before the sample reached failure.

In general, it can be noted that the stress-strain relationships exhibit a linear portion, then as micro-cracking takes place, the shape of the curve becomes increasingly non-linear until it reaches the maximum stress. From Figures (4.9) and (4.10), the followings can be illustrated:

i. Figure (4.9) clearly shows that the initial slope of the first portion of the stress-strain curves with the same w/c decrease as the PET ratio increases. On the other hand, concerning the difference between samples confined and unconfined in this part, confined specimens behavior is nearly similar to the corresponding unconfined samples, as shown in Figure (4.10), as the confining impact is at this point negligible due to the slight lateral concrete dilation.

ii. The transitional zone of stress-strain curves, as shown in Figure (4.9), becomes lower as the substitution content increase, due to low compressive strength. On the other hand, concerning the difference between samples confined and unconfined in this part, as shown in Figure (4.10), for most confined specimens, an ascending bilinear shape is found in the transition zone.

iii. Figure (4.9) clearly shows that the second part of the stress-strain curves is characterized by an ascending trend because the confining pressure increases rapidly due to the rapid increase in lateral dilation of the concrete once internal cracks are formed. Also, an increase in axial strain and decrease in lateral strain of concrete (reverse the behavior of unconfined concrete at the same replacement ratio). This is probably because of the wrapping effect and lower strength of concrete. On the other hand, regarding the difference between specimens confined and unconfined, as shown in Figure (4.10), the slope of this part of the stress-strain curves increases with the wrapping presence. In addition, failure typically occurs at greater axial and lateral strain values than the unwrapped specimens.

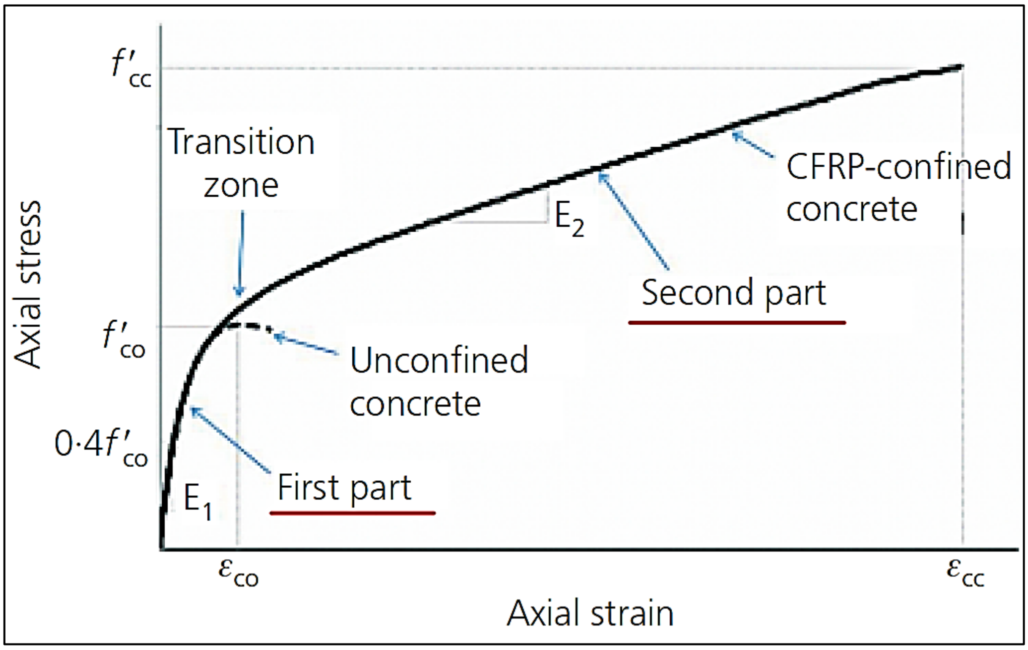

Figure 4.8: Typical stress-strain curve of CFRP-confined concrete. Adapted from [124].

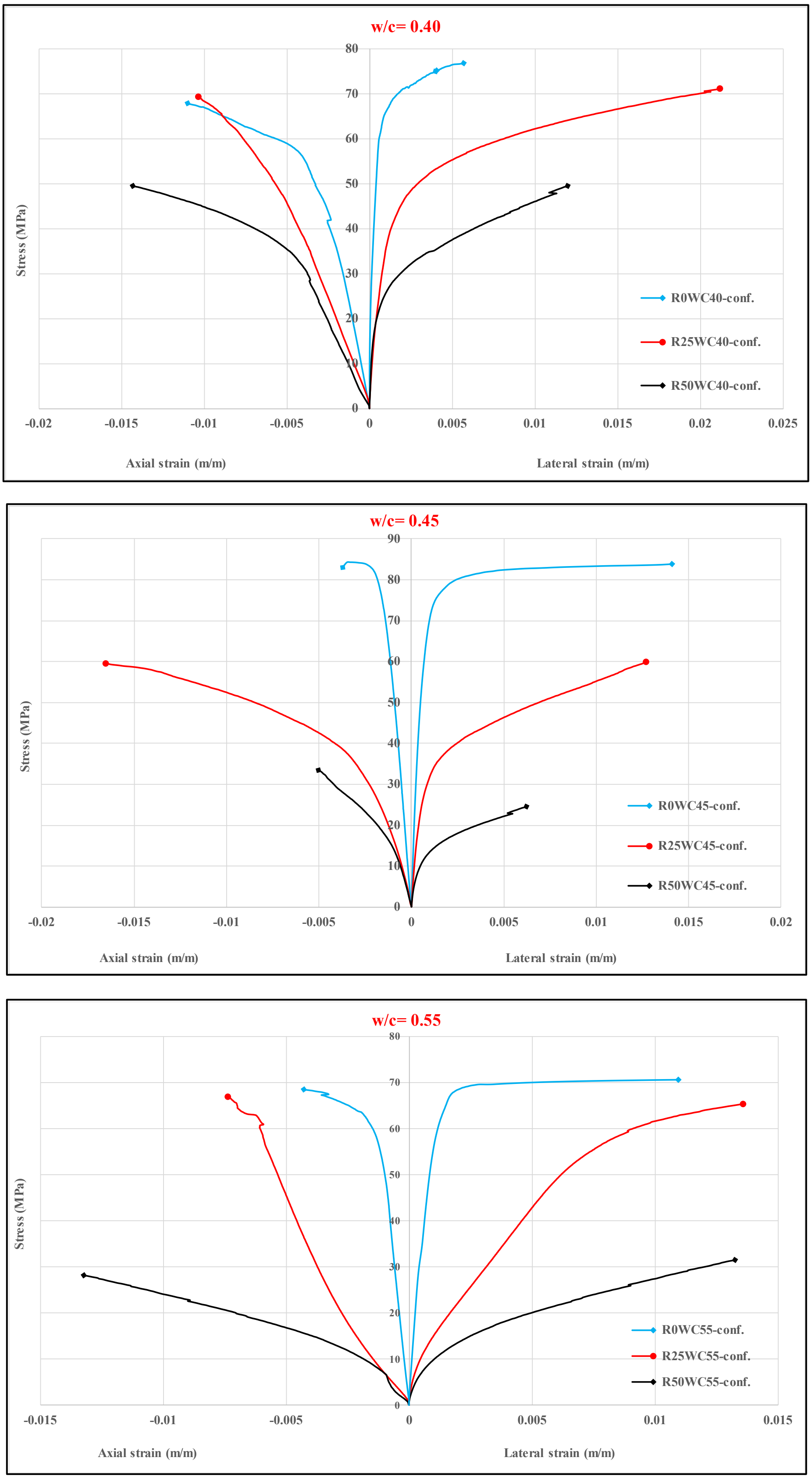

Figure 4.9: Stress-strain curves of confined specimens with different w/c.

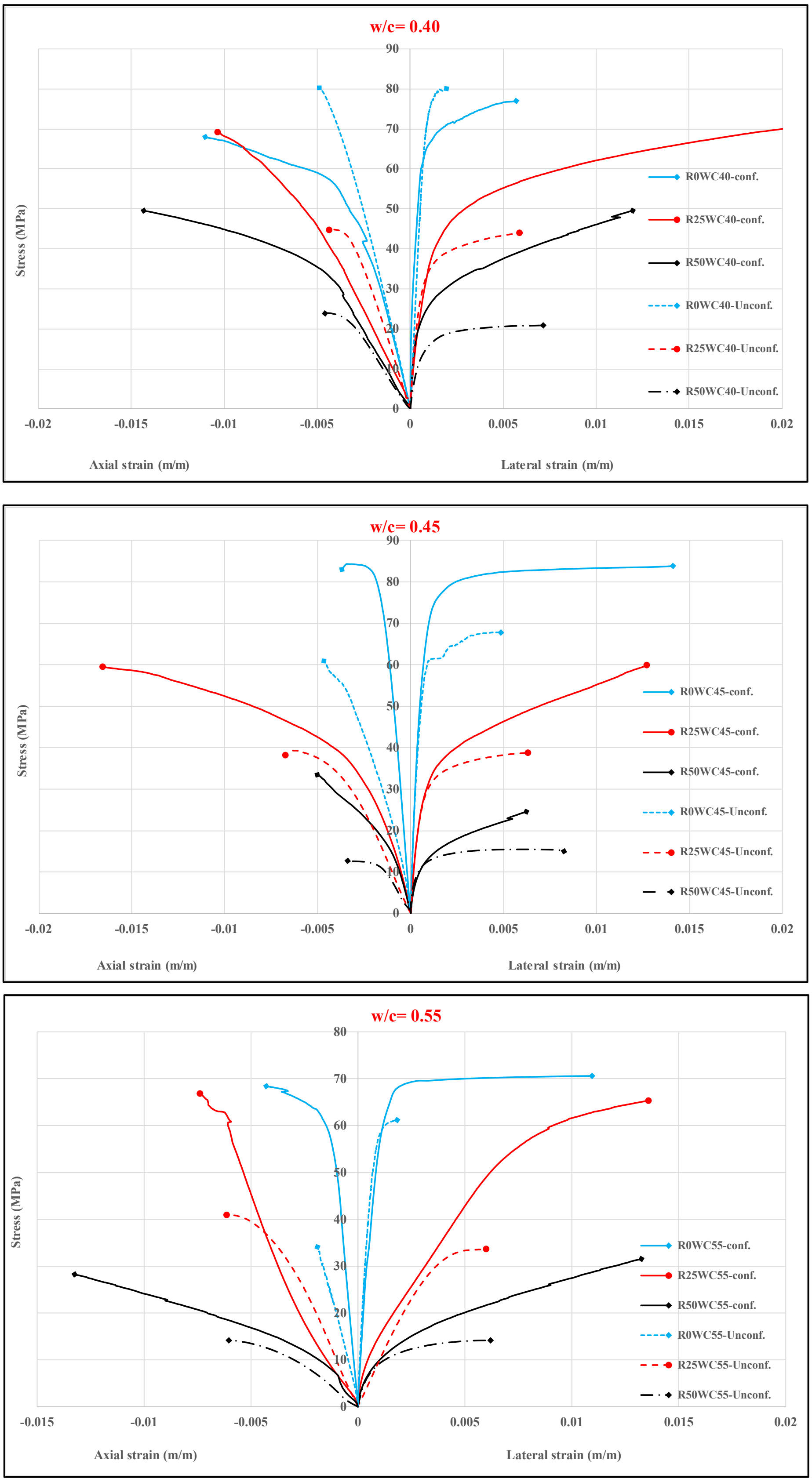

Figure 4.10: Stress-strain curves of confined and unconfined specimens with different w/c.

4.3.3 Effect of CFRP Wrapping on Strength Enhancement

To understand the effect of wrapping concrete containing plastic aggregates with various w/c ratios on the compressive strength behavior of concrete at 90-days, the experimental results are presented in Table (4.4), section 4.3. Regardless of the replacement ratio of PET and w/c ratios, one layer of CFRP fabrics with full wrapping led to significant enhancement of the ultimate compressive strength of PET-concrete cylinders compared to that of the unwrapped cylinders. Such strength increase can be explained by the fact that confinement has greatly served its purpose with PET-concrete.

On the other hand, as shown in Table (4.4) and Figure (4.11), one can note that when the proportion of w/c reduced (an increase in strength), the enhancement in strength efficiency significantly decreases. In other words, the effect of CFRP wrapping is more significant for samples with low compressive strength compared to those of higher strength samples. The reason for that is, the concrete core might expand more experiencing higher axial strain since CFRP will restrict the dilation before rapture. Also, it is noted that the efficiency of the strength enhancement increases significantly with the increase in the percentage of substitution of PET aggregates. The preceding reason for this behavior can also be extended.

Overall, the strength of cylinders containing PET aggregate and wrapped with one layer of CFRP fabric was significantly enhanced, as shown in Figure (4.11). This indicates that it is possible to enhance and recover the lost strength that resulting from inserting plastic into concrete, by using CFRP fabrics. For instance, at full CFRP wrapping with replacement rate of 25%, the strength was enhanced (recovered) by 58.9% (89.82%) (for w/c of 0.40), 66.4% (98.26%) (for w/c of 0.45), and 87.8% (140.47%) (for w/c of 0.55). While, enhancement (recovery) in strength at replacement rate of 50%, was 133.2% (50.93%) (for w/c of 0.40), 120% (51%) (for w/c of 0.45), and 190.3% (74.27%) (for w/c of 0.55).

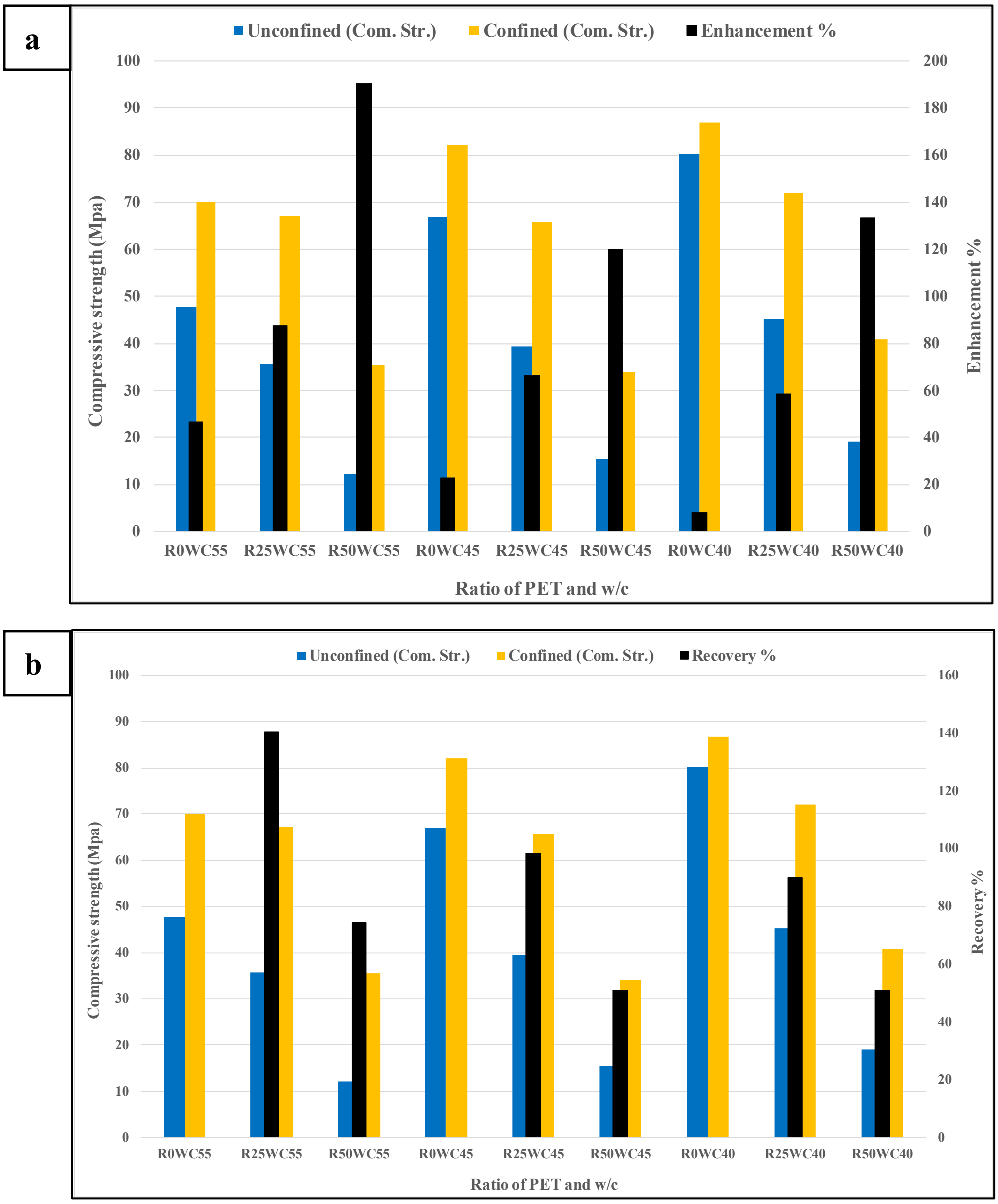

Figure 4.11: Effect of CFRP wrapping on strength: (a) enhancement; and (b) recovery.

4.3.4 Failure Modes for Confinement Specimens

The failure modes for some of the tested cylinders that are wrapped with CFRP fabrics are shown in Figure (4.13). It has been observed, at low load intensities an intermittent sound is heard, this is related to microcracking in the concrete matrix. Before the load reached its ultimate level, several sounds were heard and were associated with the rupturing of fibers within the CFRP matrix. Finally, there is a sudden bang and the CFRP sheets split into rings.

Overall, all wrapped cylinders failed by a sudden rupture of the CFRP jacket closed to the mid-height region outside the overlapping zone in an acoustic emission manner with sudden explosive as the CFRP sheet suffered excessive tension in the hoop direction. Also, accompanied by good crushing of the concrete after rupturing the CFRP sheets. Besides, it was noted that none of the confined cylinders failed at the lap location, indicating adequate adhesion and efficient load transfer between the CFRP and the concrete substrate. On the other hand, two extra observations were noticed for CFRP-confined cylinders that contain plastic aggregates, especially the high percentage of PET (50%), compared to their counterparts without PET, are: (i) the acoustic emission is less severe; and (ii) the tear of the CFRP fabric is also less severe. This behavior, as this study has already mentioned previously when describing failure modes of specimens in splitting test, is possible because of the existence of plastic particles at the failure starting point, in this location, plastic particles withstand a part of the stress applied to them before being isolated from other materials, because of its high flexibility as well laminate structure and elongated form. In other words, plastic aggregate could act as a bridge between the two separate parts.

(a): 0% PET

(b): 25% PET

(c): 50% PET

Figure 4.12: Failure modes for confinement specimens.

4.4 Relationship Between PET-Concrete Properties

4.4.1 Relationship Between Compressive and Splitting Tensile Strengths

Figure (4.14) shows the relationship between compressive strength and splitting tensile strength of the concrete at 90 days, for various PET proportions and w/c ratios. Besides, it compares the relationship with that of other studies Neville and Brooks [72], ACI-318-19 [125]. Based on Figure (4.14), correlation follows a direct relationship, the related experimental expression derived from this analysis is;

$$f_t = 0.3968 f_c^{0.62} \qquad \text{4-1}$$

The empirical relations of [72, 125], respectively, are expressed as:

$$f_t = 0.23 f_c^{0.67} \qquad \text{4-2}$$

$$f_t = 0.56 f_c^{0.5} \qquad \text{4-3}$$

As shown in Figure (4.14), it was observed that Eq. (4.3) of ACI-318-19 [127] gives a ratio closer to (Eq. 4.1), as it appears to have reduced the tensile strength of the split. While Eq. (4.2) that proposed by Neville and Brooks [72] underestimate considerably the split tensile strength of the respective PET substitution.

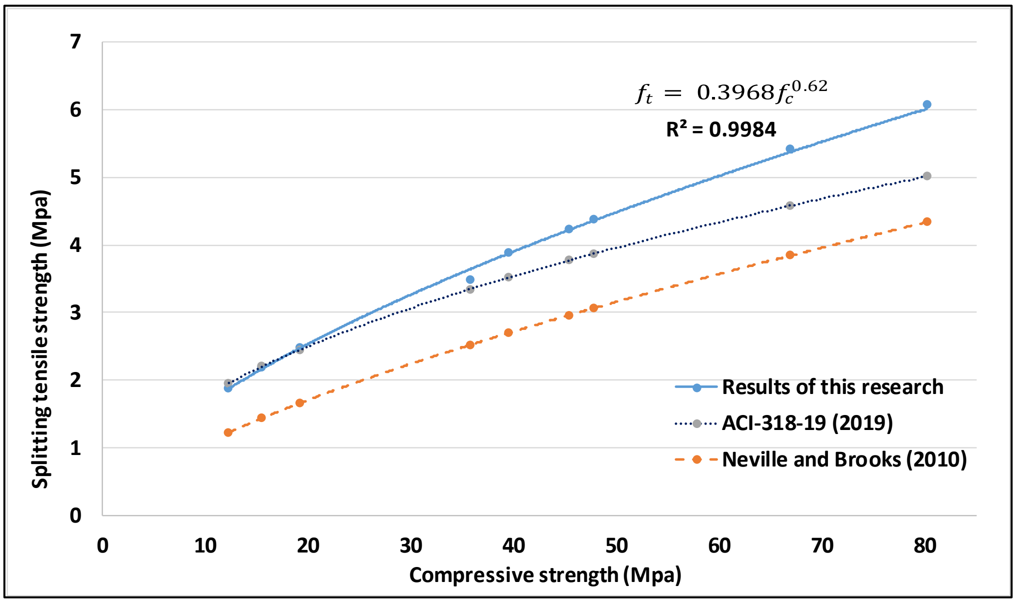

Figure 4.13: Relationship between compressive and splitting tensile strengths.

4.4.2 Relationship Between Compressive Strength and Ultrasonic Pulse Velocity

Figure (4.15) shows the relationship between compressive strength and UPV at 7, 28, and 90 days, for various PET proportions and w/c ratios. It can be noted that the compression strength increases with an increase in ultrasonic speed for all w/c ratios. The experimental data are correlated to the equation:

$$f_c{'} = 30.47V - 85.714 \qquad 4\text{-}4$$

Where (V) is the ultrasonic pulse velocity, and ($f_c{'}$) is the compressive strength. Moreover, the coefficient of determination (R^2) equals 0.95, thereby indicating a strong correlation.

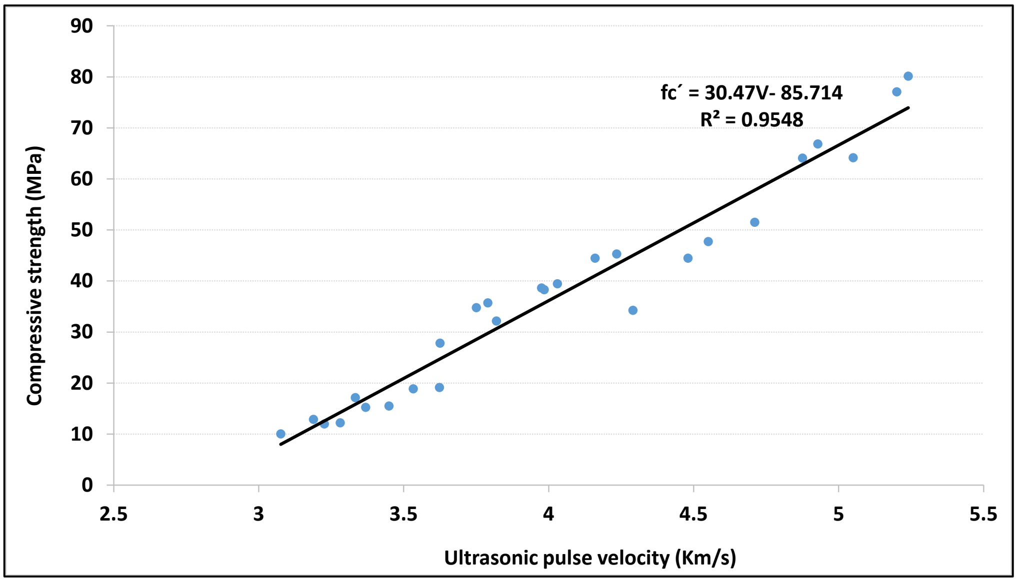

Figure 4.14: Relationship between compressive strength and ultrasonic pulse velocity.

4.4.3 Relationship Between Compressive Strength and Thermal Conductivity

Figure (4.17) shows the relationship between compressive strengths and thermal conductivity at 28 days, for various PET proportions and w/c ratios. It observed a direct relationship between them since R^2 is 0.955.

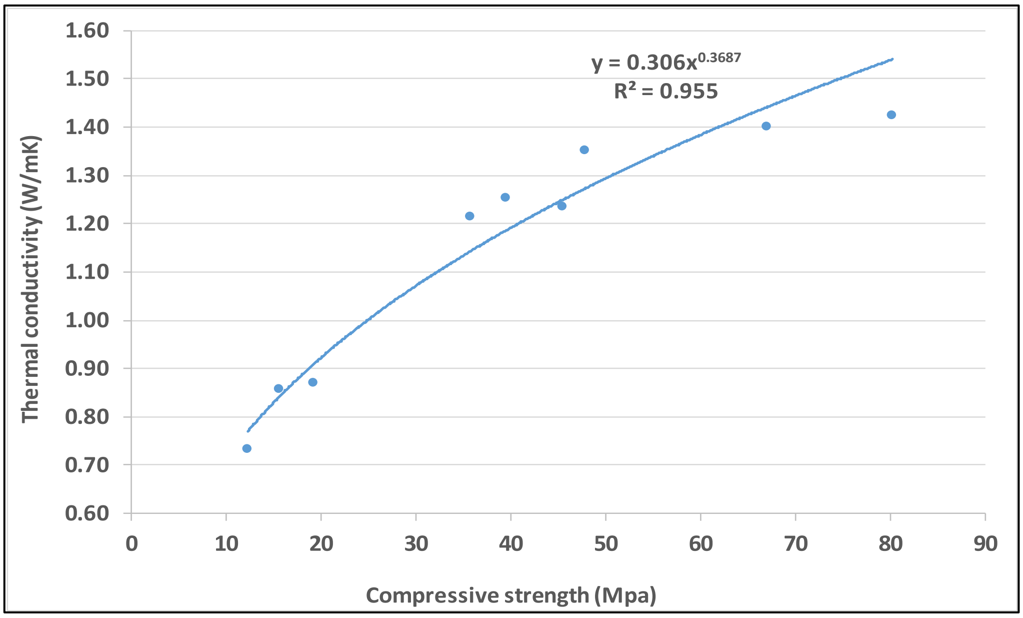

Figure 4.15: Relationship between compressive strength and thermal conductivity.

4.4.4 Relationship Between Compressive Strength and Curing Time

Figure (4.16) shows the relationship between compressive strength and curing time at 7, 28, and 90 days, for various PET proportions and w/c ratios. In general, the rate of strength, for the concrete-PET and the reference concrete, has a similar pattern. The majority of mixes of PET-concrete were able to produce approximately 75-90% of their corresponding 28-day strength at 7 days. Accordingly, it is close to reference concrete.

Even so, it was found that the early development of the PET-concrete strength was slightly different from that of the reference concrete. In Figure (4.16), the strength comparison showed that the PET concrete mixtures developed within (75-90 %) of their 28 days strength in 7 days. In contrast, reference concrete developed within (70-80 %). This behavior has also been studied by Tang, et al. [52], who mentioned that the probable cause could be due to the introduction of a polystyrene (PS) aggregate, which would reduce the capacity of the specific thermal concrete resulting in a reduced heat loss to the ambient medium during the hydration process. Tang, et al. [52] based his conclusion on the investigation of Wang, et al. [126] who carried out a calorimetric test to calculate the temperature history of freshly concrete made from polystyrene aggregate for 72 hours. Overall, it can be concluded that concrete with a PET aggregate can have a superior accelerated early age because of the greater and faster heat produced during hydration.

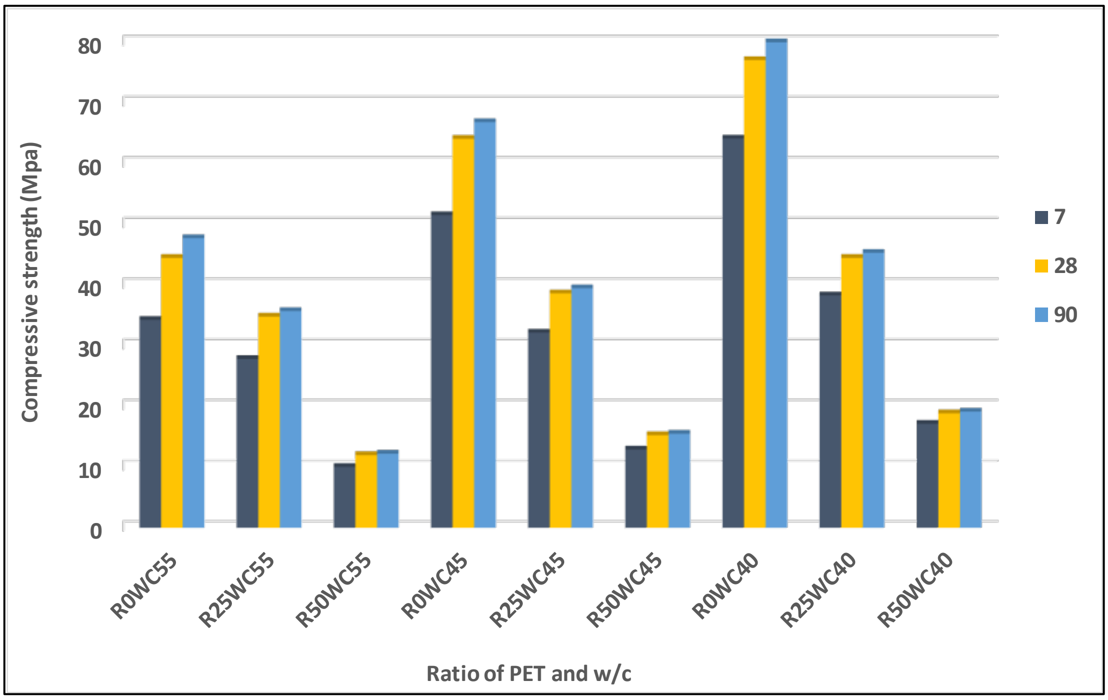

Figure 4.16: Relationship between compressive strength and curing time.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

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5.1 Conclusions

This chapter presents the main conclusions of this study which is divided into two sections. The first section focuses on the behavior of green sustainable concrete utilizing recycled PET aggregate in concrete mixes; while the second section focuses on how concrete containing PET behaves with the presence of CFRP fabrics, as follows:

5.1.1 Behavior of Concrete Containing PET Plastic Aggregate

1. Regardless of the w/c ratio, increasing the amount of plastic aggregate as a partial substitute for sand reduces the workability of fresh concrete compared to the reference mixture. This is due to the increased surface area, irregular shape, and impermeable nature of the plastic particles. Moreover, it could be used in situations requiring low-grade workability such as partition wall panels.

2. There is a decline in the fresh density and dry density of PET-containing concrete with the increase of the substitution ratio and the w/c ratios. This is attributed to lesser density of PET compared with natural sand. Moreover, concrete with 50% plastic aggregate at a ratio of 0.40-0.55 of w/c, its dry density was lower than 2000 kg/m^3. Accordingly, this concrete could be classified as a lightweight structural concrete.

3. There is an increase in the percentage of both water absorption and porosity, for the concrete containing PET aggregate with the increase of the substitution ratio and w/c ratios. This is due to the insufficient mixing of plastic and natural aggregates in the concrete matrix as a result of the smooth surface and irregular shape of the plastic aggregate. However, the high absorption property of PET-concrete can may be used in some applications that require high water drainage, for example, pavements.

4. With an increase in the PET replacement ratio and w/c ratios, the compressive strength of all PET-concrete mixtures decreased compared to the reference concrete at all curing stages. Therefore, it is recommended to use the PET-

concrete in non-structural applications (when the strength of the control mix is within the strength of normal concrete), with a replacement ratio of no more than 25%. There are several factors responsible for this decrease, the most important of which is (i) weakness of the ITZ due to the smooth surface and flat shape of plastic particles; and (ii) the hydrophobic nature of the PET particles limited water from entering the concrete microstructure during the curing process. Thus, reduced cement hydration.

5. Similar to the behavior of compressive strength, the incorporation of any ratio of plastic aggregate lowers the splitting tensile strength of concrete. As a result, the previously stated causes for reduced compressive strength may be applied to these behaviors. This incorporation considerably changes the failure behavior of the resulting concrete. This concrete is more ductile than conventional concrete and it can arrest the cracks generated during mechanical failure of concrete.

6. It could be concluded from the stress-strain curves that, with increasing PET content, the maximum strain increases significantly, and the ductility behavior improved due to the high flexibility of the plastic particles, but compared to conventional concrete, the peak compressive stress was less.

7. With the increase in the proportion of PET particles and w/c ratios, the ultrasonic pulse velocity decreased at all curing ages. Because of the high porosity of PET-concrete and laminate structure (angularity) of plastic particles. However, this property could be exploited by using it as a suitable structural material to absorb sound.

8. With the increase in the proportion of PET particles and w/c ratios, there was a considerable reduction in thermal conductivity. As compared to natural aggregate, PET aggregate had a lower thermal conductivity. Also, due to the development of a large number of cavities in the concrete structure containing PET aggregate. However, these composites could be utilized in applications as filler, like concrete masonry unit cavities.

5.1.2 Behavior of Concrete Containing PET Aggregates and Confined with CFRP Fabrics

As mentioned earlier, concrete that contains PET can be used for non-structural purposes, that do not require high compressive strength as it acts as lightweight concrete. The response of concrete containing PET aggregates and confined with CFRP fabrics was studied in this thesis. The following is the conclusion of the studied characteristics:

1. Increasing the PET aggregate ratio for cylinders confined with CFRP fabrics led to significantly increased the maximum strain. Besides, a decrease in the slope of the first part, and the peak of transition region of the stress-strain curves as a result of the decrease in strength caused by the presence of plastic aggregates. On the other hand, the second part of the stress-strain curves is characterized by an ascending trend because the confining pressure increases rapidly due to the rapid increase in lateral dilation of the concrete.
2. All samples confined with CFRP fabrics for all mixtures showed a significant enhancement in strength compared to non-confined samples for the same proportions of substitution. The enhancement ratio ranged between 8% to 190%.
3. A single layer of CFRP fabrics with complete wrapping increased the ultimate load of samples that had lost compressive strength to a level like unconfined samples without PET plastic waste (control). The recovery ratio ranged from 51% to 140%.
4. All confined samples failed due to tensile rupture of the CFRP fabrics, in which the failure spot was close to the mid-height region outside the overlapping region.
5. Based on the laboratory findings and the above description, PET plastic aggregate may be used as a partial substitute for sand for structural purposes, with a substitution ratio of up to 50% by volume, using confinement with CFRP fabrics, considering the durability characteristics.

5.2 Recommendations

Based on the findings of this study and a review of previous research, this study suggests the following for future research:

1. There is a need for further studies on the properties of concrete containing plastic aggregates, for both fine and coarse aggregate, with replacement rates higher than 50%.
2. The durability of concrete made of PET aggregates in terms of resistance to freezing and thawing, creep, and shrinkage needs further investigations.
3. Studying the effect of thickness of PET aggregates on concrete properties.
4. Investigating the techniques on how to increase the strength of the interface between PET particles and cement paste.
5. A study of confining concrete containing PET plastic aggregate with partial wrapping with CFRP sheets. Besides, conducting studies on the efficiency of confinement with multiple layers of CFRP fabrics.
6. Evaluating the feasibility of using existing models to predict the strength and strain at peak stress of concrete made of PET and confined with FRP materials. Also, studying the development of a new model for concrete containing plastic aggregates and confined with CFRP fabrics.

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APPENDIX

APPENDIX A

Summary of Previous Studies on FRP-Confined Concrete Design-Oriented Models

Table A.1 Summary of previous studies on FRP-confined concrete design-oriented models. Adapted from [89].

#	References and Year	Type of Confinement	Strength at the Peak
1	Fardis and Khalili [127]	GFRP	$f'_{cc} = f'_{co}\left[1 + 4.1\frac{f_l}{f'_{co}}\right]$ Adopted from Richart, et al. [92] $f'_{cc} = f'_{co}\left[1 + 3.7\left(\frac{f_l}{f'_{co}}\right)^{0.86}\right]$ Adapted from Newman and Newman [88]
2	Saadatmanesh, et al. [128]	GFRP & CFRP	Mander, et al. [129] $f'_{cc} = f'_{co}\left[-1.254 + 2.254\sqrt{1 + 7.94\frac{f_l}{f'_{co}}} - 2\frac{f_l}{f'_{co}}\right]$
3	Karbhari and Gao [130]	FRP	$f'_{cc} = f'_{co}\left[1 + 3.1\nu_c\left(\frac{2E_{frp}t_{frp}}{DE_c}\right) + \left(\frac{f_l}{f'_{co}}\right)\right]$
4	Samaan, et al. [131]	FRP	$f'_{cc} = f'_{co} + 6.0(f_l)^{0.7}$

(continued next page)

5	Miyauchi, et al. [132]	GFRP	$f'_{cc} = f'_{co}\left[1 + 2.98\left(\frac{f_l}{f'_{co}}\right)\right]$
6	Saafi, et al. [133]	GFRP & CFRP	$f'_{cc} = f'_{co}\left[1 + 2.2\left(\frac{f_l}{f'_{co}}\right)^{0.84}\right]$
7	Spoelstra and Monti [134]	GFRP & CFRP	Approximate analytical uniaxial model $f'_{cc} = f'_{co}\left[0.2 + 3\left(\frac{f_l}{f'_{co}}\right)^{0.5}\right]$
8	Toutanji [135]	GFRP & CFRP	$f'_{cc} = f'_{co}\left[1 + 3.5\left(\frac{f_l}{f'_{co}}\right)^{0.85}\right]$
9	Xiao and Wu [136]	CFRP	$f'_{cc} = f'_{co}\left[1.1 + \left(\frac{f_l}{f'_{co}}\right)^{0.85}\right]$
10	Lin and Chen [137]	GFRP & CFRP	$f'_{cc} = f'_{co} + 2f_l$
11	Lam and Teng [138]	GFRP & CFRP	$f'_{cc} = f'_{co}\left[1 + 2\left(\frac{f_l}{f'_{co}}\right)\right]$
12	Ilki, et al. [139]	CFRP	$f'_{cc} = f'_{co}\left[1 + 2.227\left(\frac{f_l}{f'_{co}}\right)\right]$
13	Lam and Teng [140]	FRP	$f'_{cc} = f'_{co}\left[1 + 2\left(\frac{f_l}{f'_{co}}\right)\right]$
14	Shehata, et al. [141]	CFRP	$f'_{cc} = f'_{co}\left[1 + 2\left(\frac{f_l}{f'_{co}}\right)\right]$

(continued next page)

15	Chaallal, et al. [142]	FRP	$\frac{f'_{cc}}{f'_{co}} = 1 + \frac{4.12}{f'_{co}} \times 10^5 k \quad , \quad k = \frac{A_{frp} \times E_{frp}}{A_{co} \times E_{co}}$
16	De Lorenzis and Tepfers [143]	FRP	Chosen the terms by Samaan et al. (1998), Toutanji (1999), and Spoelstra and Monti (1999), 'approximate' model
17	Lam and Teng [98] Lam and Teng [90]	FRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3\frac{f_{l,a}}{f'_{co}}$
18	Ilki, et al. [144]	CFRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.4\left(\frac{f'_{lmax}}{f'_{co}}\right)^{1.2}$
19	Bisby, et al. [145]	FRP	$f'_{cc} = f'_{co}\left[1 + 2.425\left(\frac{f_l}{f'_{co}}\right)\right]$ $f'_{cc} = f'_{co}\left[1 + 2.217\left(\frac{f_l}{f'_{co}}\right)^{0.911}\right]$ $f'_{cc} = f'_{co} + 3.587 f_l^{\,0.84}$
20	Tamuzs, et al. [146]	CFRP	$f'_{cc} = f'_{co}\left[1 + 4.2\left(\frac{f_l}{f'_{co}}\right)\right]$
21	Harajli [147]	CFRP	Mander, et al. [129]
22	Ilki, et al. [148]	CFRP	Ilki, et al. [144] & Mander, et al. [129]
23	Matthys, et al. [149]	CFRP, GFRP, and hybrid FRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.3\left(\frac{f_l}{f'_{co}}\right)^{0.85}$

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24	Berthet, et al. [150]	GFRP & CFRP	$f'_{cc} = f'_{co} + k_1 f_l$ $k_1 = 3.45 \; if \; 20 \; MPa \leq f'_{co} \leq 50 \; MPa$ $k_1 = \frac{9.5}{(f'_{co})^{\frac{1}{4}}} \; if \; 50 \; MPa \leq f'_{co} \leq 200 \; MPa$
25	Youssef, et al. [151]	GFRP & CFRP	$f'_{cc} = f'_{co}\left[1 + 2.25\left(\frac{f_l}{f'_{co}}\right)^{1.25}\right]$
26	Rousakis and Karabinis [152]	GFRP & CFRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 0.5\left(\frac{\rho_f E_f}{f'_{co}}\right) k_1 \varepsilon_{je}$ $\varepsilon_{je} k_1 = 2\left(-0.4142 E_f \times \frac{10^{-6}}{E_{f\mu}} + 0.0248\right), where \; E_{f\mu} = 10 MPa$
27	Fahmy and Wu [153]	FRP	$f'_{cc} = f'_{co} + 4.5 \, f_l^{\,0.7} \quad if \; f'_{co} \leq 40 \; MPa$ $f'_{cc} = f'_{co} + 3.75 \, f_l^{\,0.7} \quad if \; f'_{co} > 40 \; MPa$
28	Benzaid, et al. [154]	CFRP	$f'_{cc} = f'_{co}\left[1 + 1.6\frac{f_l}{f'_{co}}\right]$
29	Lee, et al. [155]	CFRP	$f_{cc} = f'_{co}\left(1 + 2\frac{f_l}{f'_{co}}\right)$
30	Ghernouti and Rabehi [156]	GFRP & CFRP	$f'_{cc} = f'_{co} + tg^2[45^o + \emptyset/2 f_l]$ $\frac{f'_{cc}}{f'_{co}} = 1 + K_3\frac{f_l}{f'_{co}}$ K_3=1.08 for CFRP and K_3=0.444 for GFRP
31	Rousakis, et al. [157]	FRP	$f'_{cc} = f'_{co}\left[1 + \left(\frac{4 t_f E_f}{d f'_{co}}\right)\left(\frac{\alpha E_f 10^{-6}}{(E_{f\mu})} + \beta\right)\right]$ $E_{f\mu} = 10 \; MPa \; for \; units' compliance$

(continued next page)

32	Ozbakkaloglu and Lim [158]	GFRP & CFRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.64\frac{f_{l,a}}{f'_{co}}$ *CFRP* $\frac{f'_{cc}}{f'_{co}} = 1 + 2.6\frac{f_{l,a}}{f'_{co}}$ *GFRP*
33	Huang, et al. [159]	GFRP	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.69\left(\frac{f_l}{f'_{co}}\right)^{0.63}$

Notation for the above Table shown in Figure (A.1), as follows:

f_l or f_{lf} lateral or effective confining pressure of FRP
$f_{l,a}$ actual confining pressure
f_{le} effective lateral confining pressure
$f'_{l\ max}$ maximum effective transverse confinement stress[33]
g parameter in model proposed by Ghernouti and Rabehi[45]
k_1 confinement effectiveness coefficient
K_3 and K_4 empirically determined confinement coefficients
k_f parameter of steel spiral confining pressure
k_s parameter of FRP confining pressure
n number of FRP layers
t_{frp} thickness of FRP wrapping
T temperature (°C)
β parameter used by Rousakis et al.[46]
ε_h, $\varepsilon_{h,rup}$, ε_{frp}, ε_l or ε_r hoop or lateral (radial) strain of the FRP wrapping
ε_{je} effective strain of jacket
ε_{he} effective strain of FRP at rupture
ε_{l1} lateral strain of concrete at f'_{c1}
v_c Poisson's ratio of plain concrete at given load level
Ø factor used by Ghernouti and Rabehi[45]
A_{co} cross-sectional area of the unconfined column
A_{frp} area of composite fibres
D or d inside core diameter of the confined concrete section
E_c initial tangent modulus of elasticity of concrete core
E_{co} modulus of elasticity of the unconfined concrete
E_f elastic modulus of fibre
E_{frp} modulus of elasticity of FRP wrapping
$E_{f\mu}$ 10 MPa[46]
f'_c peak (maximum) compressive axial stress of concrete
f'_{co} maximum compressive strength of unconfined concrete
f'_{cc} maximum compressive strength of confined concrete
f_{frp} tensile stress in FRP wrapping

Figure A.1: Notation for the Table (A.1).Also, adapted from Al-Kamaki, et al. (2015) [90].

APPENDIX B

Design of Concrete Mixtures

B.1 Introduction

The process of calculating the required and specific characteristics of a concrete mix is known as a mix design. Characteristics can involve: (i) fresh concrete characteristics; (ii) mechanical properties of hard concrete, such as requirements for strength and durability; and (iii) relevant ingredient inclusion, omission, or limitations.

In this appendix, the process of design of concrete mixtures were applied according to the specifications of [111] and [125], by following the procedures adopted from the book "Design and Control of Concrete Mixtures" (Chapter 9 - Designing and Proportioning Normal Concrete Mixtures) by [160].

B.2 Brief Mix Design Procedures

1. **Finding f'_{cr}** = average of compressive strength required for the basis of selecting concrete proportions. Table (B.1) was used to obtain it when data is not available to create a standard deviation.

Table B. 1: Required Average Compressive Strength. Adapted from ([125], [160]).

Specified compressive strength, f'_c, MPa	Required average compressive strength, f'_{cr}, MPa
Less than 21	$f'_c + 7.0$
21 to 35	$f'_c + 8.5$
Over 35	$1.10 f'_c + 5.0$

2. **Choice of slump:** workability is the consistency of fresh concrete mixture that identifies how simple and homogeneous it can be mixed, set, unified, and finished, whereas slump is used to calculate fresh concrete mixes workability or consistency. Table (B-2) demonstrates the general slump scope for specific applications.

Table B. 2: Recommended Slumps for Various Types of Construction. Adapted from ([111], [160]).

Concrete construction	Slump, mm (in.)	
	Maximum*	Minimum
Reinforced foundation walls and footings	75 (3)	25 (1)
Plain footings, caissons, and substructure walls	75 (3)	25 (1)
Beams and reinforced walls	100 (4)	25 (1)
Building columns	100 (4)	25 (1)
Pavements and slabs	75 (3)	25 (1)
Mass concrete	75 (3)	25 (1)

3. **Maximum aggregate size:** factors are governing the use of the maximum size of coarse aggregate. In this study, it was not addressed because it was not available, in which the maximum size was chosen in advance.

4. **Admixtures**: used to improve some of the desired properties, ensure quality, and reduce the cost of concrete. In this study, superplasticizers have been used to enhance workability, which in turn also minimize water content between 12% to 30%, and some can simultaneously increase air content to 1%; Some else may or may not impact air content.

5. **Mixing water and air content:** the quantity of mixing water needed to produce concrete in a unit volume depends upon the quantity of coarse aggregate, shape, and maximum size aggregate. Larger sizes decrease the water requirement and thus reduce the cement content. Table (B.3), shows the approximate mixing of water and target air content.

Table B. 3: Approximate water and air amount material criteria for various slumps and nominal maximum aggregate sizes. Adapted from ([111], [125], [160]).

Slump, mm	Water, kilograms per cubic meter of concrete, for indicated sizes of aggregate*							
	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm**	75 mm**	150 mm**
	Non-air-entrained concrete							
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
	Air-entrained concrete							
25 to 50	181	175	168	160	150	142	122	107
75 to 100	202	193	184	175	165	157	133	119
150 to 175	216	205	197	184	174	166	154	—
Recommended average total air content, percent, for level of exposure:†								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

6. **W/c ratio:** indicates the proportion of water to Portland cement. Unless durability does not govern, the proportion of water to cementitious materials (w/cm) should be chosen in terms of the concrete compressive strength. Table (B.4) can be used to pick a w/cm proportion.

Table B. 4: Relationship between the compressive strength of concrete and w/cm ratio. Adapted from ([111], [160]).

Compressive strength at 28 days, MPa	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
45	0.38	0.30
40	0.42	0.34
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

7. **Cement Content:** the content of cementing materials is mainly measured by the water content and selected w/c ratio. Moreover, a minimum and maximum cement content ratio is often included in the specifications. The criteria for minimum cement content guarantee sufficient durability and finish ability. Table (B.5) indicates the minimum cementing content criteria used in flatwork.

Table B. 5: Minimum cementing material requirement used in concrete flatwork. Adapted from ([111], [160]).

Nominal maximum size of aggregate, mm (in.)	Bulk volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate*			
	2.40	2.60	2.80	3.00
9.5 (⅜)	0.50	0.48	0.46	0.44
12.5 (½)	0.59	0.57	0.55	0.53
19 (¾)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (1½)	0.75	0.73	0.71	0.69
50 (2)	0.78	0.76	0.74	0.72
75 (3)	0.82	0.80	0.78	0.76
150 (6)	0.87	0.85	0.83	0.81

8. **Coarse aggregate content:** the coarse aggregate bulk volume can be estimated from Table (B.6), and its dependent on dry-rodded aggregates condition as defined in ASTM C29 [102].

Table B. 6: The coarse aggregate bulk volume (m³). Adapted from ([111], [160]).

Nominal maximum size of aggregate, mm (in.)	Cementing materials, kg/m³ (lb/yd³)*
37.5 (1½)	280 (470)
25 (1)	310 (520)
19 (¾)	320 (540)
12.5 (½)	350 (590)
9.5 (⅜)	360 (610)

9. **Fine Aggregate Content:** calculated from the absolute volume proportioning method, this includes the use of specific gravity values for all components to measure the absolute volume each of them would occupy in a unit volume of concrete.

10. **Adjustments for Aggregate Moisture:** aggregate volumes are determined based on dry oven unit weights, but the aggregate is usually batched based on actual weight. Thus, any moisture in the aggregate will lead to increasing its weight. This results in a net change in the water quantity available in the mixture and must be balanced by changing the volume of added water.

B.3 Mixture Design and Proportioning for This Study

The mixture design and proportioning for this study are summarized in Table (B.7), depending on the steps and procedure mentioned previously.

Table B. 7: Summary of mixture design and proportioning for this study.

Grade M20 (w/c 0.55)	Grade M30 (w/c 0.45)	Grade M40 (w/c 0.40)
1. f'_{cr}= 27 MPa	**1.** f'_{cr}= 38.5 MPa	**1.** f'_{cr}= 49 MPa
2. Slump = selection (100 ±10) mm for reference concrete (0% PET) only.	**2. Slump** = selection (100 ±10) mm for reference concrete (0% PET) only.	**2. Slump** = selection (100 ±10) mm for reference concrete (0% PET) only.
3. M.S.A*= M.N.A*= 19mm	**3. M.S.A* = M.N.A*** = 19mm	**3. M.S.A* = M.N.A*** = 19mm
4. Admixture = superplasticizers, reduce water contents 15% (according to manufacturing)	**4. Admixture** = superplasticizers, reduce water contents 15% (according to manufacturing)	**4. Admixture** = superplasticizers, reduce water contents 15% (according to manufacturing)
5. Water Content= 205-(15% SP) = 205–(0.15x205)= 174 Kg/m^3 **Air content** = 2%	**5. Water Content**= 205-(15% SP) = 205–(0.15x205)= 174 Kg/m^3 **Air content** = 2%	**5. Water Content**= 205-(15% SP) = 205–(0.15x205)= 174 Kg/m^3 **Air content** = 2%
6. w/c = selection (0.55), according to Table (B.4), and w/c ratio employed in past research [24], that ranged from (0.40 to 0.56).	**6. w/c** = selection (0.45), according to Table (B.4), and w/c ratio employed in past research [24], that ranged from (0.40 to 0.56).	**6. w/c** = selection (0.40), according to Table (B.4), and w/c ratio employed in past research [24], that ranged from (0.40 to 0.56).
7. Cement content= (174/0.55) = 316, selection 320 Kg/m^3 (According Table (B. 5))	**7. Cement content**= (174/0.45) = 387, selection 387 Kg/m^3 (According Table (B. 5))	**7. Cement content**= (174/0.40) = 435, selection 435 Kg/m^3 (According Table (B. 5))
8. Coarse aggregate content= 0.62x1540 = 955 Kg/m^3	**8. Coarse aggregate content**= 0.62x1540 = 955 Kg/m^3	**8. Coarse aggregate content**= 0.62x1540 = 955 Kg/m^3
9. **Fine Aggregate Content**= 0.34x2.7x1000 = 940 Kg/m^3	9. **Fine Aggregate Content**= 0.326x2.7x1000 = 880 Kg/m^3	9. **Fine Aggregate Content**= 0.329x2.7x1000 = 888 Kg/m^3
10. **Adjustments for Aggregate Moisture:** **C.A**= 955 Kg/m^3 (not change, because moisture content for C.A =0)	10. **Adjustments for Aggregate Moisture:** **C.A**= 955 Kg/m^3 (not change, because moisture content for C.A =0)	10. **Adjustments for Aggregate Moisture:** **C.A**= 955 Kg/m^3 (not change, because moisture content for C.A =0)

F.A = 940 Kg/m^3(not change, because moisture content for F.A =0) 11. **Trial mixes**: many trial mixtures were conducted to choose the optimum dose of superplasticizer for slump (100mm), founded SP= 8.8 g / 1 Kg of cement.	**F.A** = 880 Kg/m^3(not change, because moisture content for F.A =0) 11. **Trial mixes**: many trial mixtures were conducted to choose the optimum dose of superplasticizer for slump (100mm), founded SP= 8.5 g / 1 Kg of cement.	**F.A** = 888 Kg/m^3(not change, because moisture content for F.A =0) 11. **Trial mixes**: Adjust Cement Content and F.A: Cement content = 460 (Kg/m^3); F.A= 861 (Kg/m^3). Many trial mixtures were conducted to choose the optimum dose of superplasticizer for slump (100±10mm) and founded SP= 9 g / 1 Kg of cement.
Adjusted Content (kg/m^3): Cement: 320 Water: 157 Gravel: 955 Sand: 940 PET: 0% SP: 2.81 A/C**: 5.92	**Adjusted Content (kg/m^3):** Cement: 387 Water: 158 Gravel: 955 Sand: 880 PET: 0% SP: 3.29 A/C**: 4.74	**Adjusted Content (kg/m^3):** Cement: 460 Water: 158.5 Gravel: 955 Sand: 861 PET: 0% SP: 4.14 A/C**: 3.94

* **M.S.A**: Maximum Size Aggregate; **M.N.A**: Maximum Nominal Aggregate;

** **A/C:** Aggregate cement ratio.

It is worth pointing out a fact regarding the increase in compressive strength results (presented in Chapter Four, Section 4.2.4) for different curing periods (7, 28, and 90 days) than design strength. This has been attributed to the following reasons: (i) the design method contained a safety factor as shown in the previous design steps; (ii) the ratio of aggregate to cement (A/C) was low and decreased with increasing strength, according to research, this has a positive influence on increasing compressive strength; and (iii) the use of admixture (superplasticizers) has the effect of increasing compressive strength albeit little.

ملخص البحث

في هذه الدراسة، تم دمج نفايات البلاستيك البولي إيثيلين تيريفثاليت (PET)، وهو نوع من البوليمر وشائع الاستخدام في تصنيع الزجاجات البلاستيكية، في الخرسانة. لذلك، فإن هدف الدراسة الحالية هو دراسة سلوك الخرسانة المحتوية على البلاستيك عن طريق دمج نفايات البلاستيك PET في الخرسانة عن طريق استبدالها جزئيًا بالركام الناعم. أظهرت الدراسات السابقة أن الخرسانة المحتوية على البلاستيك تقتصر عادةً على التطبيقات غير الهيكلية بسبب خصائصها المنخفضة القوة. كما هو معروف جيدًا، فإن استقرار الهيكل وقوة تحمله وسلامته يعتمد إلى حد كبير على خصائص مقاومة الانضغاط للخرسانة. لذلك، فإن الدراسة الحالية هي محاولة لتطوير فئة هيكلية تحتوي على ركام نفايات بلاستيكية بنسب عالية من الاستبدال، مع وجود أقمشة CFRP المستخدمة لحصر الخرسانة.

أجريت دراسة تجريبية بصب واختبار 117 أسطوانة خرسانية و54 مكعب خرساني. تم تصميم خليط خرساني حيث تم استبدال الركام الناعم جزئيًا بنفايات بلاستيك PET. كان حجم الجسيمات قريبًا من حجم الرمل المستبدل بنسبة 0٪، 25٪، 50٪، وبنسب ماء / أسمنت مختلفة 0.40، 0.45، 0.55. تم تقييم الخواص الفيزيائية والميكانيكية والمتانة والتي اشتملت على اختبارات الهطول، والكثافة الطازجة، والكثافة الجافة، وقوة الانضغاط، وقوة الانشطار، ومنحنى الإجهاد والانفعال، وسرعة النبض بالموجات فوق الصوتية، وامتصاص الماء، والمسامية، والتوصيل الحراري. لاحقاً، تم إجراء اختبارات مقاومة الانضغاط، ومنحنى الإجهاد والانفعال على أسطوانات ملفوفة بطبقة واحدة من أقمشة CFRP.

تظهر نتائج الاختبار تدهورًا في كل من الخصائص التالية: الهطول (انخفاض بنسبة 33-91٪)، وقوة الانضغاط (انخفاض 25-77٪)، وقوة الانشطار (انخفاض بنسبة 20-60٪)، ونبض الموجات فوق الصوتية السرعة (نقصان 17-31٪)، امتصاص الماء (زيادة 41-181٪)، المسامية (زيادة 35-96٪). زاد تدهور هذه الخصائص مع زيادة محتوى الركام البلاستيكي ومحتوى الماء. أظهرت النتائج أنه مع زيادة محتوى الركام البلاستيكي ونسبة الماء إلى الأسمنت، انخفضت الكثافة الرطبة والجافة أكثر، وباستخدام PET بنسبة 50 ٪، أصبحت الكثافة الجافة أقل من 2000 كجم/م ^{3}، وبالتالي تم تصنيفها على أنها الخرسانة خفيفة الوزن. أيضًا، عن طريق دمج البلاستيك في الخرسانة، تغير كسر الخرسانة من هشاشة إلى أكثر مرونة مقارنة بالخرسانة المرجعية. انخفضت الموصلية الحرارية بشكل ملحوظ (11-47٪)، وباستخدام 50٪ من البولي إيثيلين تيرفثالات، أصبحت الموصلية الحرارية أقل من (0.71 وات / م كلفن)، وبالتالي صنفت على أنها عازل تحمل. باختصار، يمكن التخلص من النفايات البلاستيكية عن طريق إعادة تدويرها إلى الخرسانة بنسب محددة (لا تتجاوز 25٪ من البولي إيثيلين تيرفثالات) للتطبيقات غير الهيكلية (عندما تكون قوة مزيج التحكم في حدود قوة الخرسانة العادية). في المقابل، عند معدلات الاستبدال العالية (50٪ من البولي إيثيلين تيرفثالات)، يمكن استخدامها في عزل المكونات الخرسانية خفيفة الوزن كما في حالة الألواح العازلة.

أظهرت النتائج أن للحصر تأثير إيجابي كبير على السلوك الانضغاطي للخرسانة PET حيث زادت كفاءة التعزيز بنسبة 8-190٪ مع زيادة نسبة الاستبدال مقارنة بالعينات غير المحصورة. أيضًا، رفعت طبقة واحدة من أقمشة CFRP القوة النهائية للعينات التي فقدت مقاومة الانضغاط إلى مستوى قريب من العينات غير المحصورة التي لا تحتوي على بلاستيك (تحكم)، حيث تراوحت نسبة الاسترداد من 51٪ إلى 140٪. تم تسجيل أقل قوة قدرها 12.21 ميجا باسكال لمزيج 0.55 من وزن / ج مع نسبة إحلال 50٪ لـ PET وزادت إلى 35.45 ميجا باسكال (استرداد 74.27٪). يترافق الحصر مع زيادة في منحدر منحنى الإجهاد والانفعال، وقد حدث الفشل عند قيم إجهاد محورية وجانبية أكبر. أيضًا، من خلال زيادة النسبة المئوية للبلاستيك، كان الانبعاث الصوتي وتمزق نسيج البلاستيك المقوى بألياف الكربون أقل حدة. بالإضافة إلى ذلك، فشلت جميع الأسطوانات المحصورة بسبب تمزق الشد لأقمشة CFRP في منطقة الارتفاع المتوسط خارج المنطقة المتداخلة. باختصار، باستخدام الحصر مع أقمشة CFRP، يمكن استخدام الركام البلاستيكي PET كبديل جزئي للرمل بنسبة استبدال تصل إلى 50٪ من حيث الحجم، للتطبيقات الهيكلية.

إقليم كوردستان - العراق

وزارة التعليم العالي والبحث العلمي

جامعة دهوك - كلية الهندسة

قسم الهندسة المدنية

سلوك الخرسانة المنتجة من نفايات PET المعاد تدويرها والمحصورة بأقمشة CFRP

رسالة

مقدمة الى مجلس كلية الهندسة في جامعة دهوك كجزء من متطلبات نيل شهادة الماجستير علوم في الهندسة المدنية - مواد البناء

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بكالوريوس في الهندسة المدنية - جامعة دهوك - 2014

بأشراف

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