# Effects of Waste Polyethylene Terephthalate as a Partial Replacement of Normal Coarse Aggregate on Fresh and Hardened Properties of Concretes

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# ABSTRACT

In this thesis, the influences of waste Polyethylene Terephthalate (WPET) fragments are studied on self-compacting concrete (SCC) fresh, physical, and mechanical properties. The substitution levels of coarse aggregates with waste PET aggregates (WPET) were 5, 10, 15, and 20 % by volume. In addition, silica fume and superplasticizer (Glenium 27) were added to the SCC mixes by 10% weight of cement and 1.75 % weight of binder respectively. L-box, V-funnel, and slump flow tests were utilized to study the mixtures workability. After assessing the physical (workability tests, weight), mechanical ($\sigma_s$, $\sigma_c$, and flexural toughness), and durability (plastic degradation at 100 and 200 °C temperatures, and UPV), the outcomes reveal that it is possible to use recycled waste PET particles as aggregates up to 20 % to produce self-compacting concrete. On the one hand, adding waste PET in SCC has negative effects on the properties of SCC, decrease in compressive strength, splitting tensile strength, flexural strength, workability and UPV. Nevertheless, the compensation of this strength loss and workability could be done by adding pozzolanic materials (silica fume and fly ash) and superplasticizers (Glenium 27). On the other hand, the use of waste PET particles as coarse aggregates has positive effects as well, when it increases the toughness of SCC and makes it more deformable, reduces the self-weight of concrete owing to its low weight, and reduces the pollution of nature.

**Keywords:** Self-compacting concrete (SCC), Polyethylene Terephthalate (PET), Silica fume, Mechanical properties, Workability.

# ÖZ

Bu deneysel çalışmada; PET şişe atıklarından elde edilmiş olan parçacıkların iri agrega yerine kullanılmasının, kendiliğinden yerleşen beton (KYB)'a; işlenebilirliği, fiziksel ve de mekanik özeliklerine olan etkileri farklı deneylerle araştırılmıştır. İri agrega yerine betona katılmış olan atık PET şişe parçacıkları toplam hacmin, %5, %10, %15, ve %20. Bunun yanı sıra; bütün karışımlara, çimento ağırlığının %10'u miktarında mikro silika, ayrıca çimento ağırlığının %1.75'i kadar da süper akışkanlaştırıcı (Glenium 27) kullanılmıştır. Elde edilen beton karışımlarının işlenebilirlik tayini için L-kutusu, V-hunesi ve çökme deneyleri yapılmıştır. Fiziksel özelikler; işlenebilirlik ve özgül ağırlık, mekanik özelikler ise; yarma mukavemeti, basınç mukavemeti, eğilme dayanımları ve tokluk deneyleri olarak sıralanır. Dayanıklılık testleri ise; beton örneklerinin 100 °C ve 200 °C sıcaklığa maruz bırakarak ve önceden yapılmış testlerin tekrarlanarak değişimin tesbit edilmesini kapsar. Atık PET parçalarının iri agrega yerine yerleştirilmesi konusu, KYB akışkanlık özeliklerini sağlaması açısından da irdelenmelidir. Bu çalışmada atık PET parçalarının iri agrega yerine en fazla %20'ye kadar yerdeğiştirmesinin mümkün olduğu yapılan KYB işlenebilirlik deneyleri ile anlaşılmıştır. Atık PET parçalarını agrega yerine kullanmak, birçok konuda betona avantaj sağlarken, bazı parametrelerde kayıba yol açtığı da bulgular arasındadır. Bunlar sırasıyle, yarmada çekme, basınç ve eğilme dayanımlarıdır. Bunun yanısıra KYB işlenebilirliğinde de azalma ve de iç çatlaklarda artiş gözlemlenebilir. Fakat, dayanım ve işlenebilirlik kayıpları uygun miktarda mikro silika, uçucu kül katılarak giderilebilir. Öte yandan, PET parçacıklarının KYB'da iri agrega yerine kullanılması betonun sünekliğini ve tokluğunu arttırması açısından, ayrıca ağırlığın azaltılması ve çevre kirliliğini azaltması açısından avantajlı olabilir.

**Anahtar Kelimeler:** Kendiliğinden yerleşen beton (KYB), Polyethylene Terephthalate (PET), İşlenebilirlik, Mikro silika, Mekanik özelikler.

# DEDICATION

Deeply, I would like to dedicate this work to my dear parents

My brothers and sisters

My lovely fiancé who supported me and stood beside me in all hard times

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I would like to thank all who helped me to fulfill this thesis successfully.

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| | |
|---|---|
| C | Cement |
| CA | Coarse Aggregates |
| FA | Fine Aggregates |
| PET | Polyethylene Terephthalate |
| SCC | Self-compacting Concrete |
| SF | Silica fume |
| W | Water |
| w/b | Water-binder ratio |
| WPET | Waste PET Bottles Aggregates |
| WPET-SCC | Waste PET Self-compacting Concrete |
| $\sigma_c$ | Compressive Strength |
| $\sigma_s$ | Splitting Tensile Strength |
| $\sigma_f$ | Flexural Strength |
| UPV | Ultrasonic Pulse Velocity |

# Chapter 1

# INTRODUCTION

## 1.1 Background of the Study

Nowadays, concrete is consumed very extensively in the world, which is a combination of cement, water, aggregates, and admixtures if necessary.

Since the earthquake loads are related to the structure mass (Kiliç et al, 2003), the need of lightweight gravel has increased steadily, because of its significant role in decreasing the weight of concrete.

These days, Lightweight concrete is produced by the application of several methods, using either artificial or natural lightweight aggregates (Topcu and Uygunoglu, 2007; Babu et al., 2005; Yasar et al., 2003; Demirboga and Gul, 2003; Malloy et al., 2001). Nevertheless, producing artificial lightweight aggregate is expensive, because of the high incineration temperature required (Topcu, 2006). Thus, production of lightweight concrete by using lightweight aggregates made from waste plastic materials has been investigated, so we can recycle the plastic waste, and make a lightweight concrete economically (Koide et al., 2002).

There are several types of plastic wastes that we can use in producing lightweight aggregates, such as: polypropylene (PP), polyethylene (PE), polystyrene (PS) and polyethylene terephthalate (PET).

Producing of PET bottles has increased rapidly because of the high consumption rate of it, where PET bottles are used today as a vessel to store water and different types of beverage instead of glass bottles, due to its lightweight, and easiness of managing and packaging. In addition, PET bottles waste need hundreds of years to degrade in the nature (Silva et al., 2005). Hence, using these wastes in other areas has been investigated to get rid of them, and minimize the environmental issue.

The substitution of polymer with cement binders may produce polymer concrete, but its production is very pricey due to the high cost of conventional resins. Thus, many researchers were focused on producing resin from waste PET bottles to use it in polymer concrete in order to decrease the price of resin produced according to the normal one. (Rebeiz et al., 1991; Rebeiz, 1995; Rebeiz and Fowler, 1996; Abdel-Azim, 1996; Tawfik and Eskander, 2006). However, producing polymer concrete from PET bottles still high.

Another method is to transform waste PET bottles into plastic fibers and use them to make fiber reinforced concrete (Silva et al., 2005; Ochi et al., 2007). But the quantity of plastic fiber that can be added to concrete is still very low (0.3 % up to 1.5 %), then it does not seem an effective way to eliminate the huge amount of waste PET bottles.

The last method that seems the most reasonable one is using waste PET bottles as plastic aggregates in concrete, so it is possible to produce lightweight concrete, eliminate the waste plastic PET bottles, decrease the environmental problem, and reduce usage of natural aggregates which in its turn reduce the distortion of nature due to the spread of aggregate’s crushers in the mountains.

Marzouk et al (2007) studied the using of PET bottles as a coordinate to the natural aggregate in concrete, and they ended up with the possibility of replacing natural fine aggregate with shredded plastic PET bottles in concrete successfully.

In recent times, self-compacting concrete (SCC) has been investigated. It is a very workable and cohesive concrete that does not need vibration after casting, due to its consolidation ability by its own weight.

Firstly, Japanese researchers searched and developed self-compacting concrete in 1980s to enhance durability and strength development of structure in Japan (Bartos, 1999; Collepardi et al., 2003; Ozawa et al., 1989; Okamura and Ouchi, 2003; Xie et al., 2002). Nowadays, SCC is mostly widespread in all over the world and applied for many structural and architectural uses.

In general, chemical materials like blast furnace slag, silica fume, and fly ash are inserted to SCC as a filler to enhance the effectiveness and performance of it (Felekoğlu et al., 2006; Sahmaran et al., 2006; Türkmen, 2003).

Finally, SCC has many advantages such as preventing noises come from vibration work, enhancing the production rate, save money by reducing man power needed, increase durability, achieve easiness of casting in the congested areas (H. Beigi et al., 2013).

## 1.2 Aim of the Research

In this study, the main aim is to find out the variations that will occur on rheological, mechanical, and physical properties of SCC when shredded waste PET granules (WPET) are added in a partial replacement of coarse aggregates at different substitution levels, for water/binder (w/b) of 0.45. The objectives to be investigated are:

1. Determining the influence of waste PET plastic aggregates on fresh concrete workability.
2. Studying the effect of PET plastic aggregate on concrete compressive strength ($\sigma_c$), flexural strength, splitting tensile strength, and ultra sound pulse velocity.
3. Studying the effect of high temperatures (100 and 200 °C) on the physical and mechanical properties of self-compacting concrete
4. Investigating the influence of PET plastic aggregate addition on flexural toughness.
5. Determining the optimum amount of coarse replacement by PET plastic aggregate.
6. Build conclusions and suggestions for future studies rely on the outcomes of the study.

## 1.3 Thesis Outline

In chapter 2, (literature review), the previous significant works on the properties of concrete have been briefly mentioned and explained. Chapter 3 (experimental process and materials) clarifies entirely the steps that have been followed in all the experiments and techniques, that were made according to the international standards. Chapter 4 (results and discussions) contains the outcomes that are concluded based on the experiments and the analysis done. In chapter 5 (conclusions), based on the outcomes in the previous chapter, several conclusions are made from this research work.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Introduction

The use of plastic has become considerably everywhere throughout the world as of late and this has made gigantic amounts of plastic based waste. Plastic waste is currently a genuine natural danger to the cutting edge method for living.

Plastic waste is not able to be buried in landfill as a result of its mass and moderate degradation rate. Reusing plastic waste to deliver new substances such as aggregate in cement may be a standout amongst other answers for discarding it, given its financial and natural preferences.

In concrete, diverse sorts of plastic waste are utilized as aggregates, fiber or filler after mechanical handling. They contain: polyethylene terephthalate (PET) bottles, polyvinyl chloride, PVC channels, high density polyethylene (HDPE), thermosetting plastics, blended plastic waste, extended polystyrene, polyurethane foam, polycarbonate, and glass reinforced plastic (Akcaozoglu S, Atis CD & Akcaozoglu K. , 2010).

Joining plastic aggregates (PA) can fundamentally enhance several concrete properties since PA has higher toughness, greater abrasion behavior, lower thermal conductivity and higher heat capacity than conventional aggregates.

Plastic aggregates are fundamentally characterized by a very light weight compared to normal aggregate (NA) and along these lines, its fuse brings down the densities of the subsequent concrete ( Saikia N &  de Brito J.,2010).

This feature could be utilized to create lightweight concrete. However, PA incorporation in concrete has some negative impacts, for example, low workability and weakening of mechanical behavior ( Saikia N &  de Brito J.,2010).

## 2.2 The Effects of Using Polyethylene Terephthalate Particles on Properties of Concrete

### 2.2.1 Physical Properties of Concrete

The workability of PET concrete is influenced by several aspects, like water-cement ratio (w/c), percentage level of PET aggregate, and the dimension of them.

Albano et al (2009) declared that the workability of concrete decreases with increasing fine aggregate replacement amount with waste PET bottles, however, it was discovered that as high as is the w/c ratio, this addition has more influences on the workability. Moreover, he claimed that as the particle size of PET is bigger, the negative influence on workability will be greater. In this study, two different w/c ratios were used (0.5; 0.6), two different substitution level of recycled PET were adopted (10 and 20 % by volume), and two different particle sizes (0.26, 1.14 cm).

On the other hand, Choi et al. (2005) declared that the slump test of fresh concrete raised from 10 to reach 22.3 cm with 75 % replacement of bottles lightweight aggregate (WPLA) which means about 123 % improvement of workability compared to the control. This may be because of the spherical and soft form of WPLA and the low absorption rate of them.

Furthermore, Sadrmomtazi et al (2016) reported that with increasing PET content, the workability of plastic lightweight self-compacting concrete (WPSCC) reduces. V-funnel time increase from 6.2 to 12.2 s, slump flow decreases from 678 to 620 mm, and L-box fraction ($H_2/H_1$) decreases from 0.94 to 0.76 when the replacement of PET content increases from 0 to 15 %, Which does not satisfy the SCC requirements according to EFNARC 2005.

Frigione (2010) found that when the substitution level of fine aggregate with waste PET bottles aggregates (WPET) is 5 % by weight, the workability is slightly lower than the conventional concrete.

Azhdarpour et al (2016) declared that the outcomes of experimental analysis demonstrated that addition of plastic particles made from PET bottles modified the physical properties of concretes. In particular, UPV and density of concrete reduced as the PET content increased.

### 2.2.2 Mechanical Properties of Concrete

Choi et al. (2005) replaced fine aggregates partially with WPET as lightweight aggregates in concrete included with granulated blast furnace slag (GBFS). It was discovered that after 28 days and with w/c ratio of 0.73 the $\sigma_c$ of specimen comprising 25 % of WPET by volume of whole mix as sand is decreased of around 6 % comparing with the conventional concrete and of around 9 % in respect to concrete with w/c of 0.45. The $\sigma_s$ reductions were 19 % for w/c of 0.73 and 15 % for w/c of 0.45.

In a later report (Choi et al., 2009), it is accounted for the utilization of lightweight aggregate manufactured from waste PET bottles (WPLA) coated with fine aggregates. WPLA aggregates demonstrated a water absorption of around 0 % that can check the deformities of normal lightweight gravels, which have great water absorption rate. When the percentage of plastic aggregate increased in the mortar, the flow of WPLA mortar increased relatively. Likewise, the mortar $\sigma_c$ had the tendency to diminish as the substitution level of WPLA augmented. After 28 days, the $\sigma_c$ of specimens made with WPLA concrete reduced by 5, 15, and 30 % compared with the conventional lightweight concrete, when the waste PET bottles aggregates percentages in the mixture were 25, 50, and 75 %, respectively.

Different investigators thought about the conduct of two distinct mortars, the primary made with just WPET aggregates and the other made with WPET and fine aggregates (Akcaozog˘lu et al., 2010). Furthermore, blast-furnace slag was likewise utilized as substitution of concrete (at half of substitution on weight premise proportion). The WPET/binder ratio and the water/binder (w/b) ratio were utilized as a part of the mixtures were 0.45 and 0.50, separately. The sizes of crushed WPET particles utilized as a part of the mortar mixtures was between 0 and 4 mm. The outcomes of the investigation demonstrated that mortar comprising just WPET, mortar comprising WPET and normal sand, and mortar replaced with slag as bond substitution could be all considered as lightweight concrete according to the strength properties and unit weight. At last, the mortar containing WPET aggregates recorded greater shrinkage rate than the mortar containing both WPET aggregate and normal sand. Notwithstanding, the quantitative connection amongst concrete and mortar can't be satisfied, for the most part.

Albano et al. (2009) dissected the mechanical properties of concrete, two different w/c ratios were adopted (0.5 and 0.6), two different substitution levels of recycled PET were used (10 and 20 % by volume), and two different plastic sizes (0.26 and 1.14 cm). The outcomes demonstrated that, as the volume extent and the molecule size of WPET expanded, WPET-filled concrete demonstrated a reduction in $\sigma_s$, $\sigma_c$, modulus of elasticity, and UPV, and augmentation in water absorption rate. It was accounted for, in any case, that the concrete samples were not completely compacted. Likewise, they demonstrated the development of pores which truly influenced the quality attributes.

Pezzi et al. (2006) added WPET in concrete as aggregate, and assessed physical and mechanical properties of mixes. The incorporation of WPET with size from 15 to 25 mm in portions up to 10 % by volume of aggregate of whole mix did not bring out critical changes in $\sigma_c$ at low w/c ratios.

Marzouk et al. (2007) explored the utilization of waste PET bottles aggregates in concrete after separating, washing, and crushing them. The substitution level of WPET was by volume of fine aggregate of the full mixture. The investigation showed that plastic particles might be effectively utilized as fine aggregates in concrete. It was at first noticed that, the $\sigma_c$ of mortar gradually diminished of around 16 %, in examination with the normal concrete when the incorporation percentage level of WPET raised from 0 to 50 %. The reduction of $\sigma_c$ achieved 32.8 %, when the replacement level reached 50 %.

Ismail and AL-Hashmi (2008) researched in concrete the likelihood of utilizing different wastes of plastic, comprising around 20 % polystyrene and 80 %

polyethylene, as sand replacement, with sizes up to 4.75 mm. The outcomes reveal that when the plastic content in concrete increased, the compressive strength had a tendency to decrease at different curing age. When the plastic waste were added by 10 %, the concrete showed the most reduced $\sigma_c$ after 28 days of curing, the loss reached around 30 % compared with the control mix.

Frigione (2010) found that when the substitution level of fine aggregate with waste PET bottles aggregates (WPET) is 5 % by weight, the loss of $\sigma_s$ is pretty low in comparison with the normal concrete (-0.02 MPa). However, this reduction was greater in the case of higher w/c ratios.

Jaivignesh and Sofi (2017) reported that when the addition of WPET increased from 10 to 20 %, $\sigma_s$ decrease from 10 to 24 % in comparison with the reference concrete. Similarly, the $\sigma_f$ reduction was in the interval of 20 to 30 %.

Sadrmomtazi et al (2016) declared that in self-compacting concrete, when the substitution level of waste PET aggregates was 5 %, and the percentage of cement replaced with silica fume was 10 %, the $\sigma_f$ of the mixture decreased up to 14.7 % comparing to the reference, at 28 days. In addition, this reduction reaches 34.6 % when WPET contents was 10 %, and with 30 % fly ash as a replacement of cement. Therefore, adding WPET to the concrete has a vital effect in decreasing $\sigma_f$ of self-compacting concrete (SCC). Similarly, waste PET aggregates in SCC mixture decrease the splitting tensile strength of concrete specimens. Expanding PET contents from 5 up to 15 % decreases the $\sigma_s$ of concrete samples around 48.8 %. They added that the ultrasonic pulse velocity (UPV) rates reduce as PET content increases since WPET increase the porosity rate of the mixtures.

Azhdarpour et al (2016) reported that $\sigma_s$, $\sigma c$, and $\sigma_f$ of specimens increased, when the replacement ratios of fine aggregate by waste PET aggregates in concrete were 5 and 10 %. However, when the substitutions level were greater than 10 % all the mechanical properties of concrete samples decreased. Therefore, using polyethylene terephthalate as aggregates enhances the mechanical properties of concrete as long as substitution level of fine aggregates with PET particles does not exceed 10 %.

### 2.2.3 Water Absorption

Akcaozog˘lu et al. (2010) detailed that Mortars containing both WPET and normal sand (M3 and M4) recorded lower water absorption than the mortars with just WPET (M1 and M2). Regardless, M1 and M2 mixes recorded lower porosity ratios than M3 and M4 mixes.

Sadrmomtazi et al (2016) reported that water absorption rates of all mixtures increased whenever WPET were added. This is because of the flat surface of PET aggregates and the limitation of hydration rate of cement in WPSCC mixtures.

Saiki and Brito (2013) declared that adding WPET up to 10 % substitution level increases the permeability of concrete samples.

# Chapter 3

# EXPERIMENTAL WORKS

## 3.1 Introduction

In accordance with the goals of the thesis, five different mixes were casted with five different replacement percentages namely 0, 5, 10, 15, and 20 % of Waste plastic PET bottles for w/b ratios of 0.45, using self-compacting concrete. The main goal was to determine the effects of plastic PET aggregates added on the fresh, physical and mechanical properties of SCC. For this reason, several tests have been made:

1. Workability test for SCC (slump flow, V-funnel, L-box)
2. Compressive strength
3. Splitting tensile strength
4. Ultrasonic pulse velocity
5. Flexural toughness
6. Degradation test, with two different temperatures 100 °C and 200 °C (Influence of temperature on $\sigma_c$, $\sigma_s$, UPV, micro-cracks, and density of concrete).

Finally, this chapter illustrates the materials used in the mixtures, the standard codes that are used in the experimental study, and the ways how the using of tools, machines, and test method have been done.

## 3.2 Materials Utilized

### 3.2.1 Cement Type

Cement used as a binder material in concrete. The most important role of cement in the concrete mix design is developing the $\sigma_c$ during time. In this investigation, CEM II/B-M (S-L) 32.5 Portland slag cement from Boğaz Endüstri ve Madencilik ltd. cement factory in North Cyprus was utilized. The properties of the cement used (CEM II) are shown in Table 3.1.

Table 3.1: Chemical and Physical Properties of the Cement Used

| Properties | Test result | Standard |
|---|---|---|
| Insoluble Residue (%) | 0.1 | EN196-2 |
| Loss on Ignition (%) | 10.9 | |
| $SO_3$ (%) | 2.2 | |
| $SiO_2$ (%) | 18.7 | |
| CaO (%) | 60.4 | |
| Free CaO (%) | 1.0 | |
| MgO (%) | 2.0 | |
| $Al_2O_3$ (%) | 4.0 | |
| $Fe_2O_3$ (%) | 2.6 | |
| Cl (%) | 0.0 | EN196-21 |
| Specific Gravity (g/cm$^3$) | 3.0 | EN196-6 |
| Fineness (cm$^2$/g) | 4007 | |

| | | | |
|---|---|---|---|
| 90 Micrometer sieve residual (%) | | 0.26 | |
| 45 Micrometer sieve residual (%) | | 5.24 | |
| w/c ratio | | 0.28 | EN196-3 |
| Initial setting time (min) | | 185 | |
| Compressive Strength (N/mm$^2$) | 2 day | 15.8 | EN196-1 |
| | 7 day | 29.9 | |
| | 28 day | 41.3 | |

### 3.2.2 Fine and Coarse Aggregates

In this experiment, two different sizes of fine aggregates 3, and 5 mm in diameter, and coarse aggregate with maximum size of 10 mm in diameter were adopted. In order to discover the graduation of coarse and fine aggregates, ASTM C136M-14 sieve analysis was done to every size, according to ASTM C33/C33M-16 standard as shown in the Figures 3.1, 3.2 and Tables 3.3, 3.4 respectively.

Specific gravity and water absorption of aggregates are illustrated in Table 3.2.

Table 3.2: Absorption Capacity of Fine and Coarse Aggregates

| Aggregate type | Absorption capacity (%) |
|---|---|
| Fine aggregate | 1.12 |
| Coarse aggregate | 1.64 |

Table 3.3: Grading of Coarse Aggregate

| Sieve size (mm) | Mass retained (kg) | Percent mass retained (%) | Cumulative percent retained (%) | Cumulative percent passing (%) | Lower-upper limits (%) |
|---|---|---|---|---|---|
| 28 | 0 | 0 | 0 | 100 | 100 |
| 20 | 0 | 0 | 0 | 100 | 100 |
| 14 | 0 | 0 | 0 | 100 | 100 |
| 10 | 0.028 | 2.8 | 2.8 | 97.8 | 85-100 |
| 5 | 0.856 | 85.6 | 88.4 | 11.6 | 0-25 |
| 2.63 | 0.106 | 10.6 | 99 | 1 | 0.5-5 |
| 1.18 | 0.01 | 1 | 100 | 0 | - |
| Pan | - | - | - | - | - |

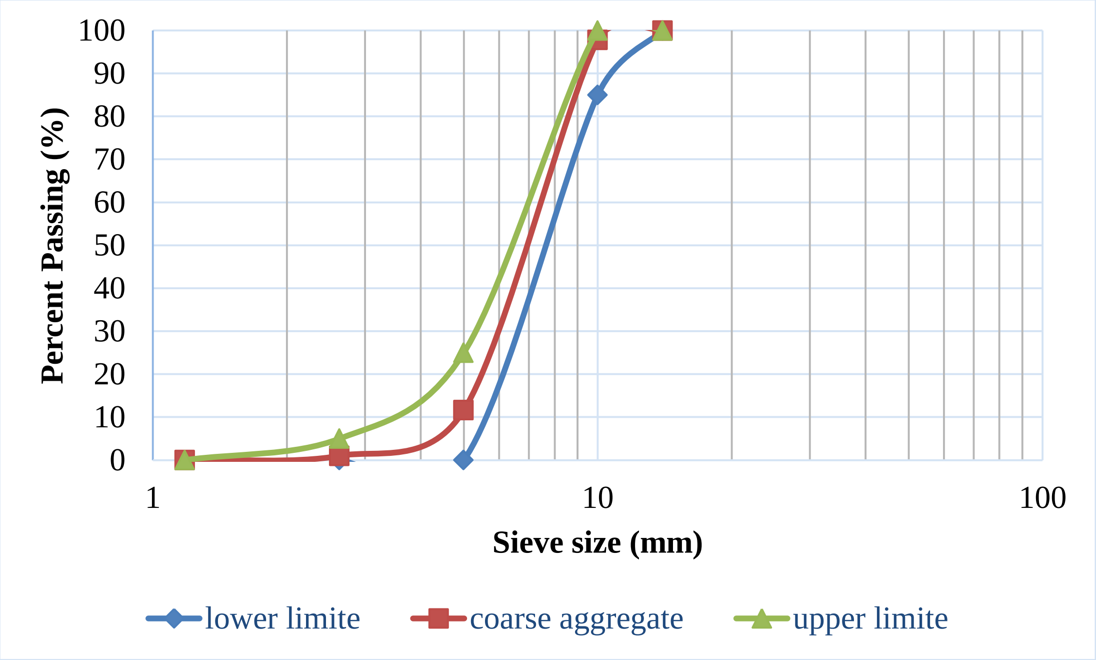


Figure 3.1: Grading Curve of Coarse Aggregate

Table 3.4: Grading of Fine Aggregates

| Sieve (mm) | Weight retained (kg) | Percent weight retained (%) | Cumulative Percent retained (%) | Cumulative Percent passing (%) | Upper-lower limits (%) |
|---|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 100 | 100 |
| 5 | 0.003 | 1 | 1 | 99 | 95-100 |
| 2.63 | 0.51 | 17 | 18 | 82 | 80-100 |
| 1.18 | 0.102 | 34 | 52 | 48 | 50-85 |
| 0.6 | 0.57 | 19 | 71 | 29 | 25-60 |
| 0.3 | 0.36 | 12 | 83 | 17 | 10-30 |
| 0.15 | 0.3 | 10 | 93 | 7 | 2-10 |
| 0.075 | 0.21 | 7 | 100 | 0 | - |

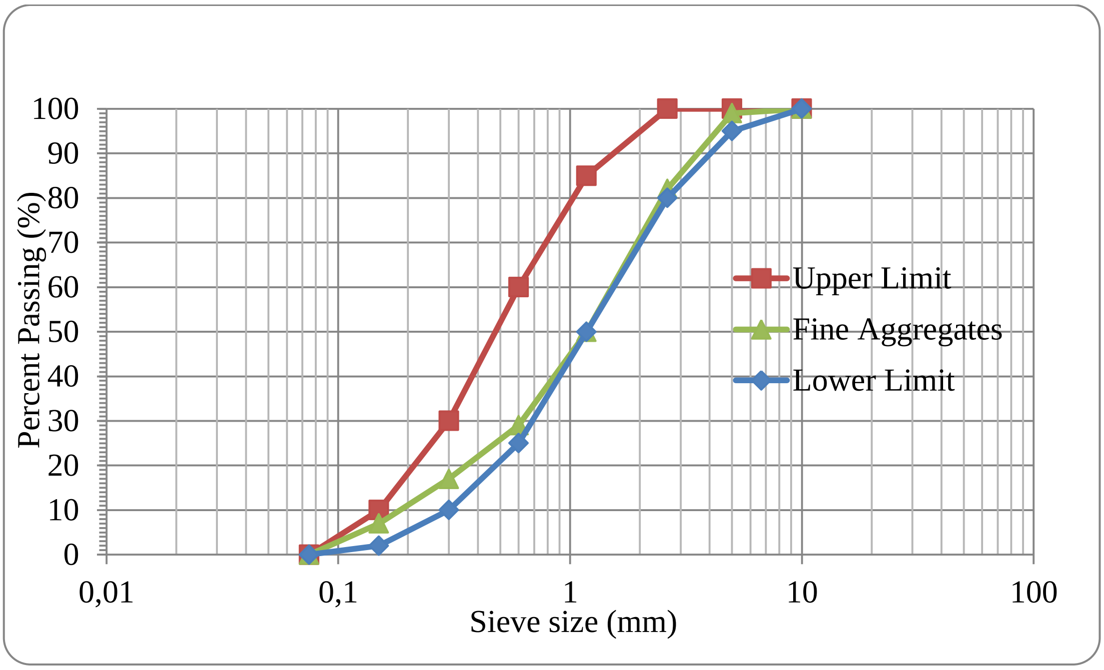


Figure 3.2: Grading Curve of Fine Aggregate

### 3.2.3 Mixing Water

For mixing and curing matters of the mixtures, potable water was utilized.

### 3.2.4 Superplasticizer

Glenium 27 was utilized in all the mixes. It is a high range water reducing admixture, based on modified polycarboxylic ether polymers, mainly used in the concrete mixes to retain the workability desired, provide high strength and durable concrete. The production of self-compacting concrete strongly depends on it, when it is used in high amount. In this study, it was used as a superplasticizer to achieve self-compacting concrete workability requirements.

### 3.2.5 Silica fume

Silica fume, also known as microsilica, (CAS number 69012-64-2, EINECS number 273-761-1) is an amorphous (non-crystalline) polymorph of silicon dioxide, silica. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. It is a pozzolanic material that added to cement to enhance the concrete properties. In this study, the percentage of silica fume added was 10 % of weight of cement. Chemical composition and physical properties of silica fume are illustrated in Table 3.5 and the particle distribution in Figure 3.3.

Table 3.5: Physical and Chemical Properties of Silica Fume Used

| Oxide | Percent (%) |
|---|---|
| $SiO_2$ | 82.2 |
| $Al_2O_3$ | 0.5 |
| $Fe_2O_3$ | 0.42 |
| CaO | 1.55 |
| MgO | 0.0 |
| $SO_3$ | 3.03 |
| $K_2O$ | 1.01 |

|  |  |
|---|---|
| $Na_2O$ | 0.31 |
| Specific surface ($m^2/kg$) | 15,000–30,000 |
| Specific gravity ($kg/m^3$) | 2.2 |
| Fineness ($m^2/kg$) | 29,000 |

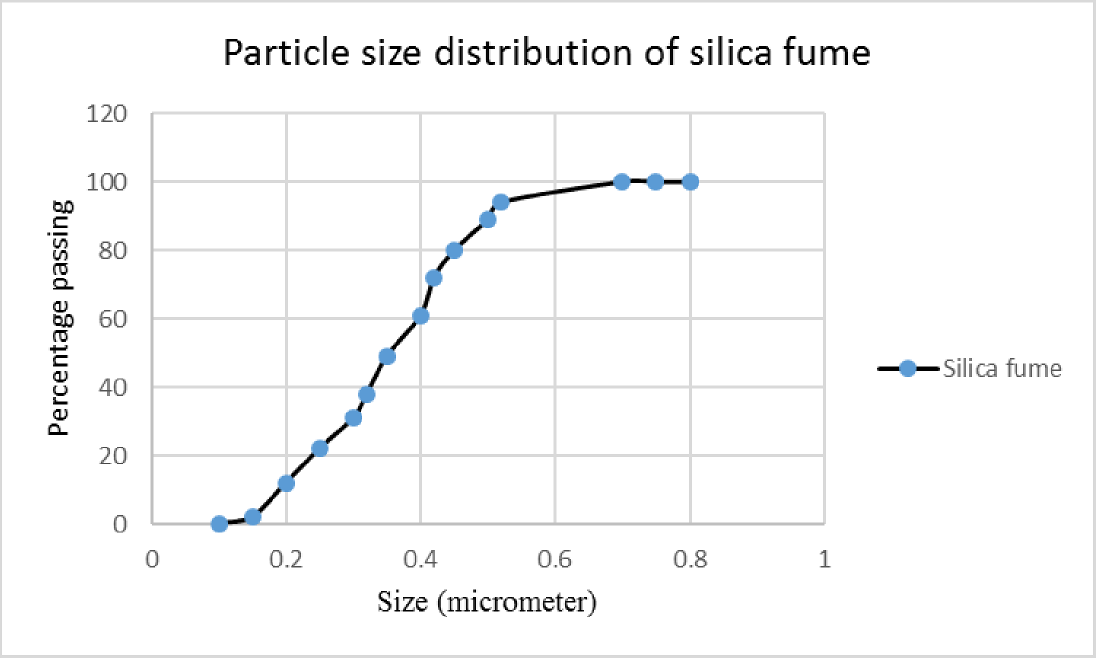


Figure 3.3: Distribution of Particle Size of Silica Fume (Amirhossein Nikdel 2014)

### 3.2.6 Waste Polyethylene Terephthalate (WPET)

Waste plastic is the surplus waste from plastic water bottles that were supplied from a plastic factory in Famagusta city (Northern Cyprus). Plastic aggregates are obtained by crushing the water bottles into small particles; its specific gravity is 1300 $kg/m^3$ (see Figure 3.4).

Figure 3.4: PET Aggregates

## 3.3 Mix Design Proportioning

Mix design is the determination of the amounts of the constituent materials of concrete mixes (cement, water, aggregates, admixtures, superplasticisers) in order to get the expected mechanical and physical properties ($\sigma_c$, permeability, durability, workability, etc.). The mix design is illustrated in Table 3.6.

Table 3.6: Mix Design Proportions and Quantities of WPET-SCC (kg/m$^3$)

| Mixture name | w/b | Water (kg) | C (kg) | SF (kg) | PA (kg) | $D_{MAX}$ 3 mm (kg) | $D_{MAX}$ 5 mm (kg) | $D_{MAX}$ 10 mm (kg) | SP (kg) |
|---|---|---|---|---|---|---|---|---|---|
| control | 0.45 | 198 | 400 | 40 | 0 | 457 | 457 | 812 | 7.7 |
| M1(5%) | 0.45 | 198 | 400 | 40 | 19.4 | 457 | 457 | 773 | 7.7 |
| M2(10%) | 0.45 | 198 | 400 | 40 | 37.7 | 457 | 457 | 737 | 7.7 |
| M3(15%) | 0.45 | 198 | 400 | 40 | 58.2 | 457 | 457 | 696 | 7.7 |
| M4(20%) | 0.45 | 198 | 400 | 40 | 77.5 | 457 | 457 | 659 | 7.7 |

PA: Plastic aggregate   C: Cement   w/b: water/binder   SF: Silica fume   SP: Superplasticiser

## 3.4 Experimental Program

Five different substitution percentages of coarse aggregates 0, 5, 10, 15 and 20 % with PA were done to investigate the influences of PA on self-compacting concrete properties. To achieve this aim, five batches were organized for the desired experiments. In the current thesis, a comparison among every replacement percentage will be done according to the control samples.

### 3.4.1 Mixing Procedure of WPET-SCC Concrete

A mixer of 0.25 $m^3$ capacity was used to mix the five concrete mixes (see Figure 3.5). First, the mixer drum surfaces were wetted by water to avoid any loss of mixtures moisture, then fine and coarse aggregates, cement, silica fume, and PET particles were inserted in the mixer and blended for approximately 45 seconds. Finally, water and superplasticizer (Glenium 27) were added to the mixture, and blended together for two minutes in order to achieve a uniform concrete mixture.

Figure 3.5: Concrete Mixer of 0.25 $m^3$ Capacity

### 3.4.2 Fresh WPET-SCC Concrete Tests

Slump flow, V-funnel and L-box tests were performed to find out filling ability (see Figures 3.6, 3.7 and 3.8, respectively), passing capacity, and segregation resistance of fresh WPET-SCC for all five different mixes percentages (0, 5, 10, 15, and 20 %). A concrete mix is considered as self-compacting concrete if the workability conditions are satisfied, based on EFNARC 2005.

The slump flow of a self-compacting concrete is proposed to be between 500 and 700 mm (Nagataki and Fujiwara, 1995). According to EFNARC 2005, V-funnel flow time should be between 6 and 12 seconds, and L-box ratio ($H_2/H_1$) varies from 0.8 to 1.

Figure 3.6: Slump Cone

Figure 3.7: V-funnel Testing Equipment

Figure 3.8: L-box Testing Equipment

### 3.4.3 Making and Curing of WPET-SCC Concrete Specimens

After fresh concrete tests, the concrete was put in the mixer again and mixed for 40 seconds.

To avoid any chemical reaction between concrete and plastic molds, and to ease the remolding process of concrete samples, oil was utilized to oil and clean the molds before casting. Then, concrete was put in the molds for twenty four hours without any vibration. Finally, the concrete specimens were placed into a curing water tank for 28 days with 20 °C temperature as shown in the Figure 3.9.

Four different kinds of specimens were created for each replacement percentages, three beams 100×100×500 mm, three cubes 150×150×150 mm, twelve cubes 100×100×100 mm, and three cylinders 100×200 mm.

Figure 3.9: Curing Tank

## 3.5 Experiments on Hardened WPET-SCC Concrete

### 3.5.1 Compressive Strength ($\sigma_c$) WPET-SCC Concrete

According to BS EN 12390-3:2009 standard specifications, compressive strength test was done at 28 days of curing, the cubic specimens (150×150×150 mm) were selected for this test, as shown in the Figure 3.10.

The test was performed on three cubes for every substitution level of WPET. The $\sigma_c$ loading speed was 0.4 MPa/s, and the maximum capacity of the compression testing machine is 3000 KN.

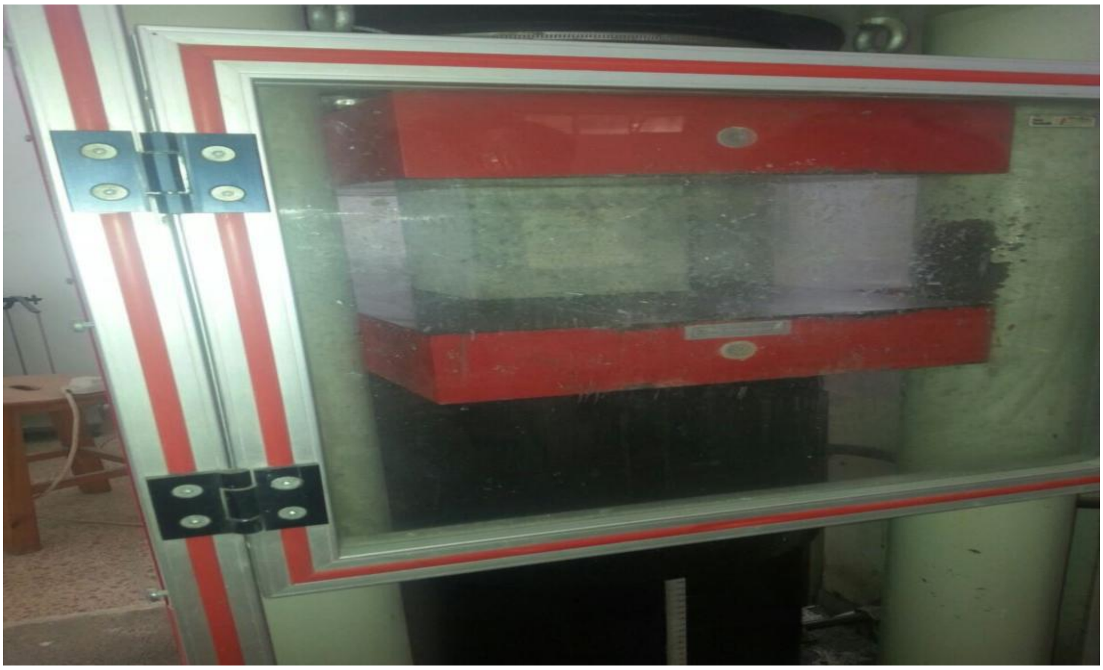


Figure 3.10: Compression Testing Machine

### 3.5.2 Splitting Tensile Strength ($\sigma_s$) of WPET-SCC Concrete

The cylindrical samples (100×200 mm) were selected and tested after 28 days of curing to investigate the influence of replacing coarse aggregate with WPET on $\sigma_s$. The experiment process was performed based on ASTM C496/C496M – 11 standards as shown in the Figure 3.11. Three cylindrical samples were broken for each substitution level of WPET in order to get more precise results.

Figure 3.11: Splitting Tensile Testing Apparatus

### 3.5.3 Ultrasonic Pulse Velocity Test (UPV) of WPET-SCC Concrete

An UPV test is a nondestructive test to evaluate the quality and the $\sigma_c$ of concrete samples. Recording the time needed by a pulse of ultrasonic wave to pass through the concrete specimens is how to recognize the strength and quality of concrete. The velocity and the concrete quality are proportional, high velocities are indicators of good quality of concrete, while low velocities signify a weak concrete contains too many cracks and voids. The cubic samples (100×100×100 mm) were prepared for this test and it was done based on ASTM C597 – 09 as shown in the Figure 3.12. After calibration of the equipment by using a standard sample of object with known pulse velocity, the transducers are placed on center of two opposite sides of the samples as illustrated in the Figure 3.12. Pulse velocity is measured by using equation 1:

$$\text{Pulse velocity (km/s)} = \frac{\text{width of concrete (km)}}{\text{time taken by pulse to pass though(sec)}} \quad (1)$$

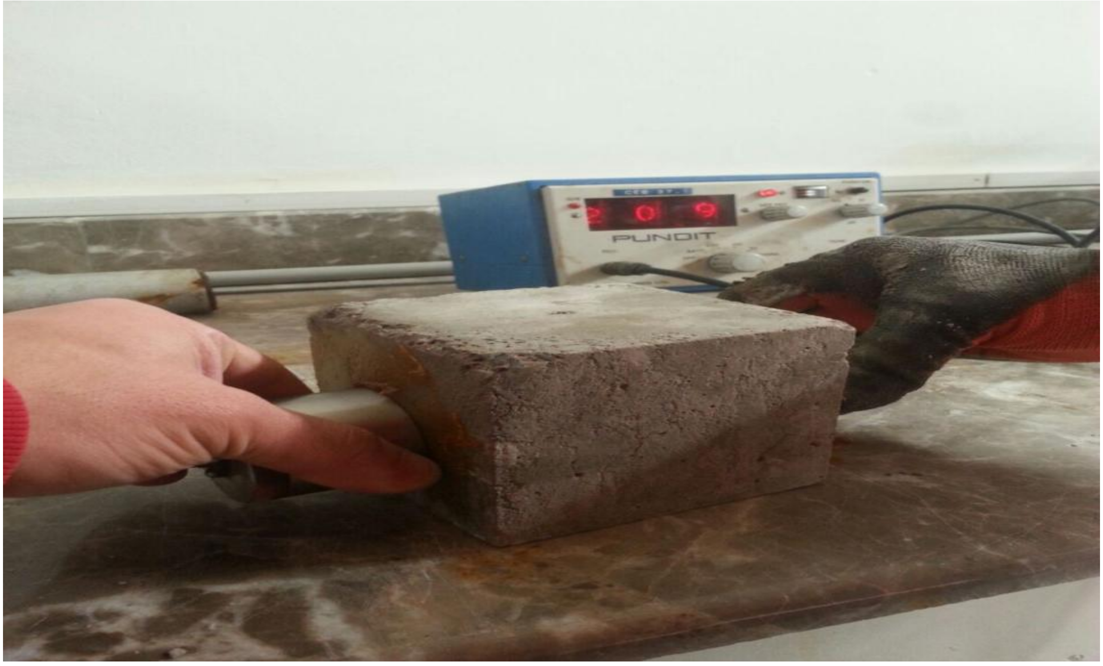


Figure 3.12: UPV Test

### 3.5.4 Resistance of WPET-SCC to Heat Exposure

This test was applied on two different temperatures namely 100 and 200 °C to study the influences of high temperatures on concrete $\sigma_c$, $\sigma_s$, density, cracks development, and UPV. For this purpose, twelve cubes 100×100×100 mm were prepared. Firstly, $\sigma_c$, $\sigma_s$, density, and ultra sonic pulse velocity were taken before putting the samples under temperature. After that, samples were placed into an oven of 200 °C capacity for four hours with an elevation rate of 10 °C /min as shown in Figure 3.13, then the oven was turned off and the samples were left to cool down for sixteen hours, then the experiments were repeated again, and the changes were recorded. In addition, a microscope was used to detect the micro-cracks development on the surfaces of heated and unheated specimens as shown in Figure 3.14.

Actually, the degradation test of PET has no standard method or ASTM or BS, to determine the procedure of it. This test was done based on an adopted method for fire resistance, and it was used by (Albano et al, 2009).

Figure 3.13: Oven of 200 °C Capacity

Figure 3.14: Stereo-Microscope

### 3.5.5. Flexural Toughness Test of WPET-SCC Concrete

In order to study the consequences of WPET on concrete micro-cracking performance, and the capacity of concrete to absorb energy before rupturing, three beams (100×100×500 mm) were prepared for each replacement percentage, and subjected to flexural loading of 0.02 mm/min, as illustrated in Figure 3.15 below. After that, load deformation diagrams were plotted, and the ductility of the samples with different replacement levels were estimated according to the estimation of the area under the curve. The maximum capacity of the flexural testing apparatus is 200 KN. This test has been performed according to ASTM C1609/C1609M.

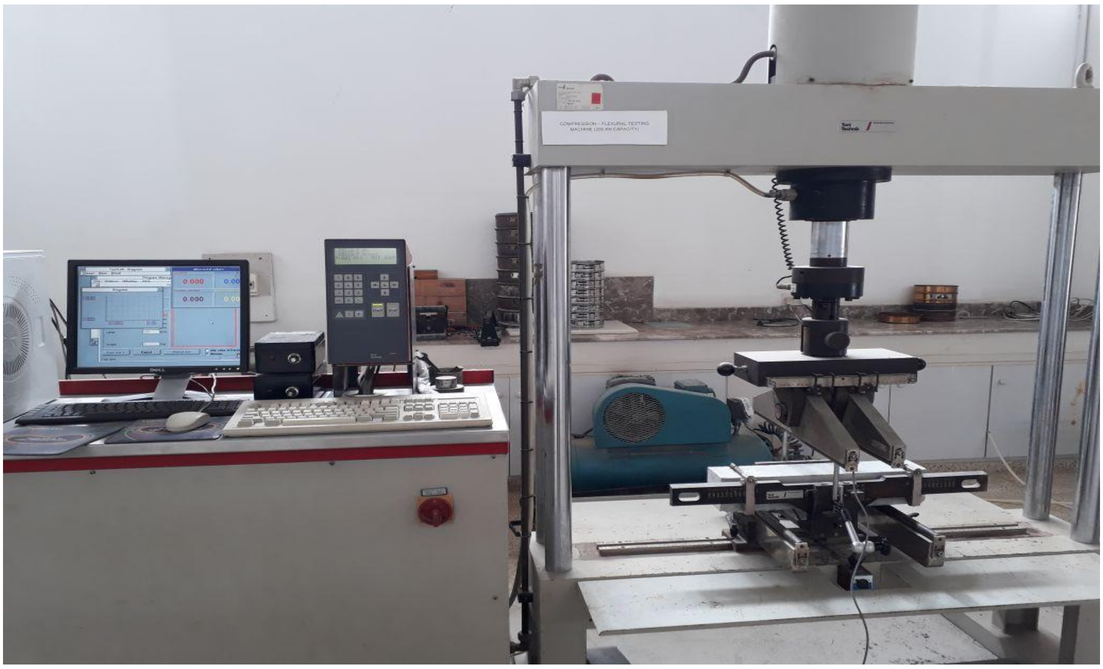


Figure 3.15: Flexural Toughness Test Arrangement with Yoke

# Chapter 4

# RESULTS AND DISCUSSIONS

## 4.1 Introduction

In this chapter, the experimental outcomes and results of five different concrete mixtures are included and discussed. Results and discussions are displayed for workability test of fresh SCC, $\sigma_c$ test, $\sigma_s$ test, flexural toughness test, ultra sonic pulse velocity test, and fire resistance test.

## 4.2 Properties of Fresh WPET-SCC Concrete

The slump flow, V-funnel, and L-box tests results of the different substitution levels of WPET by coarse aggregates 0, 5, 10, 15, and 20 % are shown in Table 4.1 and Figures 4.1, 4.2, and 4.3 respectively. The results show that as PET content in the mix increased, the workability of WPET-SCC has a tendency to decrease.

For the slump flow, Figure 4.1 illustrates that the loss of workability reached 26 % for 20 % replacement in compared with the control mix, except for 5 % replacement, the slump showed a slight increase when it reached 700 mm.

For V-funnel, Figure 4.2 shows that the time was 7 seconds in the control mixture, and it started to increase to reach 12 seconds for 20 % replacement, which indicates that the concrete took more time to empty the V-funnel.

For L-box test, Figure 4.3 shows that the ratio ($h_2/h_1$) decreased from 1 in the control mix, to reach 0.8 for 20% WPET replacement.

These could be due to the form of PET aggregates where they stick together and affect negatively the SCC rheological properties.

Nevertheless, in all mixes, concrete still within the range of workability requirements, and satisfied the SCC conditions that are mentioned in the previous section. However, the mix of 25 % replacement did not satisfy the SCC conditions even though the amount of glenium was increased to 3 %, the concrete segregated very badly due to the high amount of superplastisizer. So just up to 20 % replacement, it is possible to produce SCC by using WPET.

Table 4.1: Influence of WPET on Workability

| Mixture type | Slump flow (mm) | V-funnel (sec) | L-box ($h_2/h_1$) |
|---|---|---|---|
| Control | 650 | 7 | 0.9 |
| M1 (5%) | 655 | 7.5 | 0.88 |
| M2 (10%) | 632 | 9 | 0.86 |
| M3 (15%) | 584 | 10 | 0.83 |
| M4 (20%) | 512 | 12 | 0.8 |

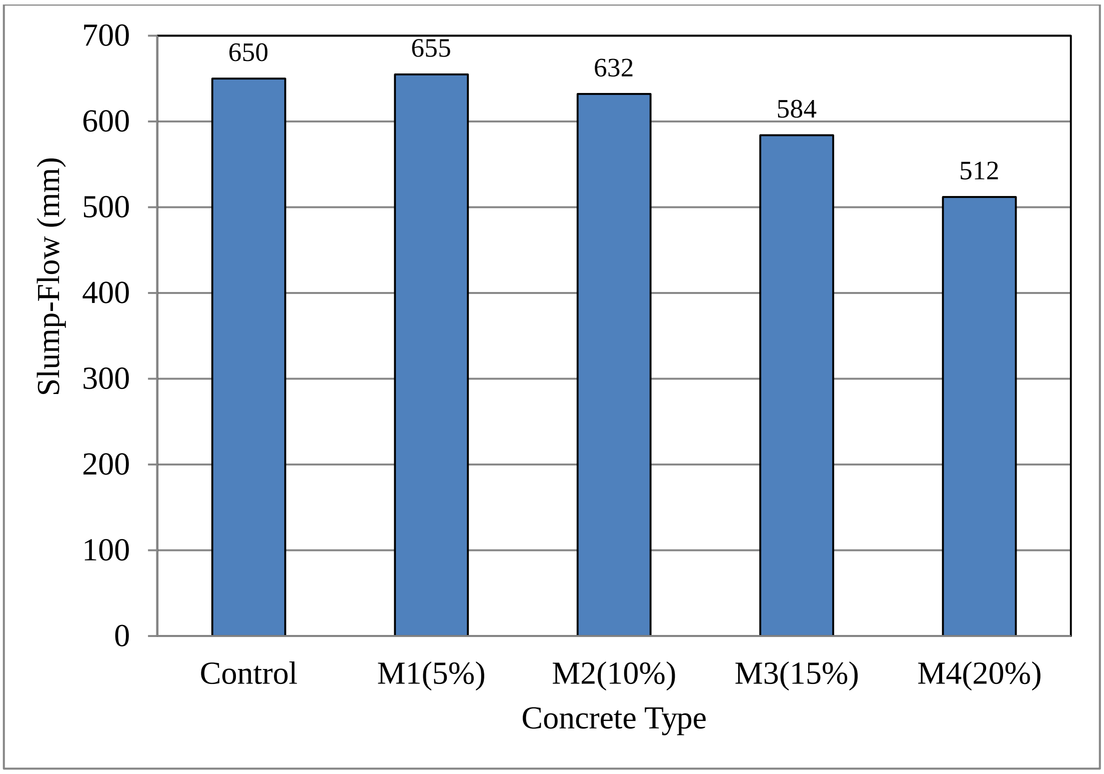


Figure 4.1: Slump Flow Test Results

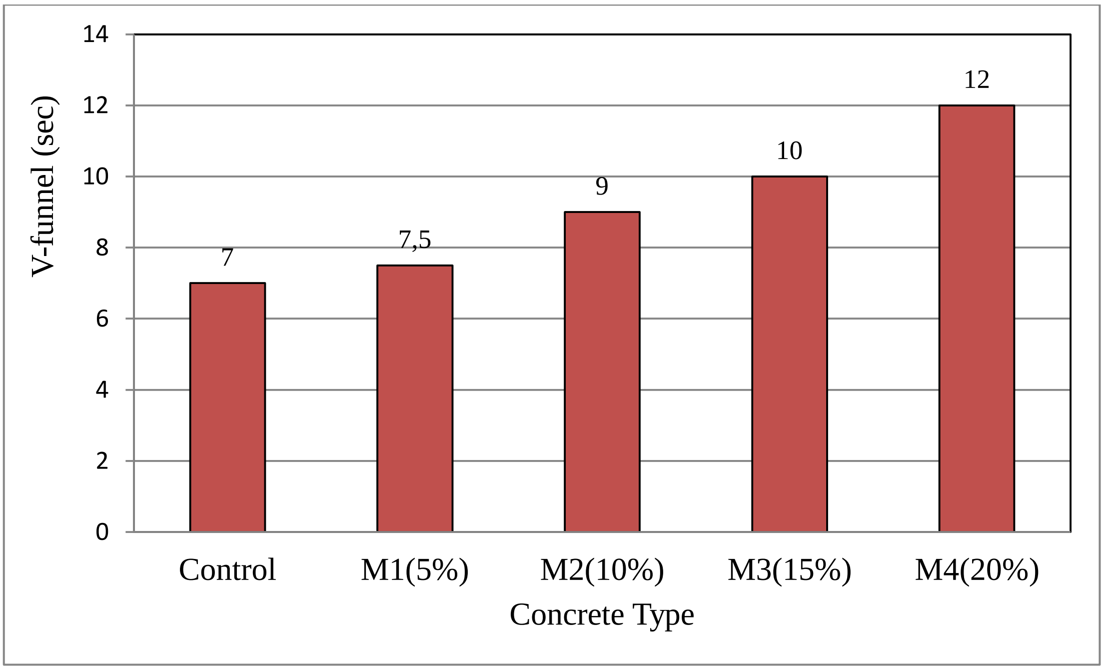


Figure 4.2: V-funnel Test Results

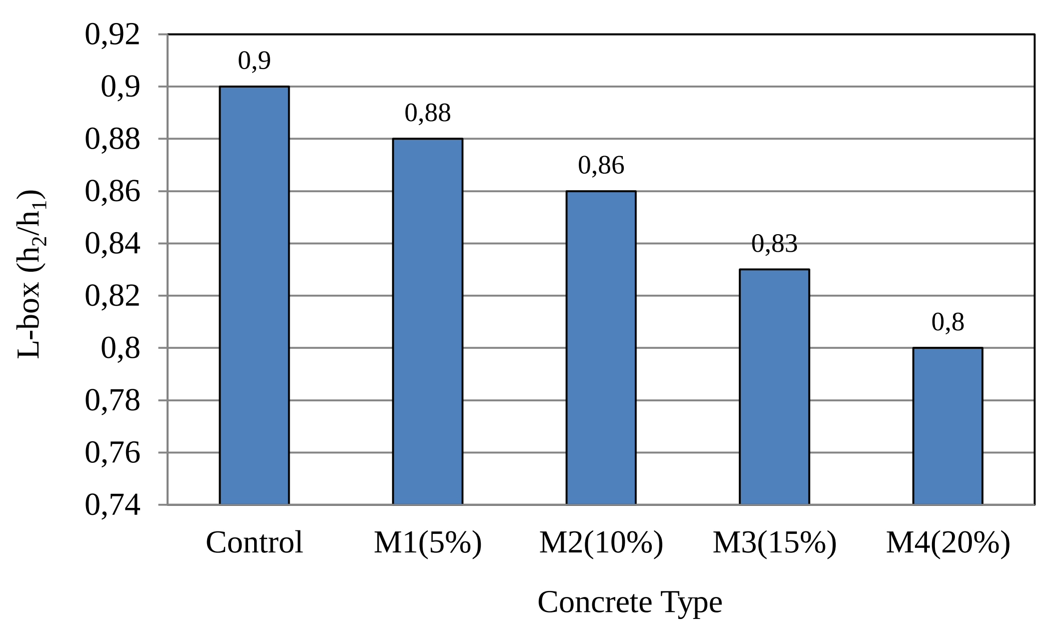


Figure 4.3: L-box Test Results

It matters to plot the regression line between the different properties of concrete which provides the ability to predict the trend of a certain test of concrete by using another known one. Figures 4.4, 4.5, and 4.6 show the linear relationships between V-funnel and slump flow, L-box and slump flow, and V-funnel and L-box, respectively. Figure 4.5 demonstrates that the increment of WPET in the mixtures decreases both L-box and slump flow value. Figures 4.4 and 4.6 show that V-funnel and slump flow, and V-funnel and L-box are not proportional, the increment of WPET in the mixes increases V-funnel time, but decreases L-Box and slump flow value. The best relationship is for the closet $R^2$ values to one, which is the V-funnel and L-box relationship with $R^2$ of 0.9815 (see Table 4.2).

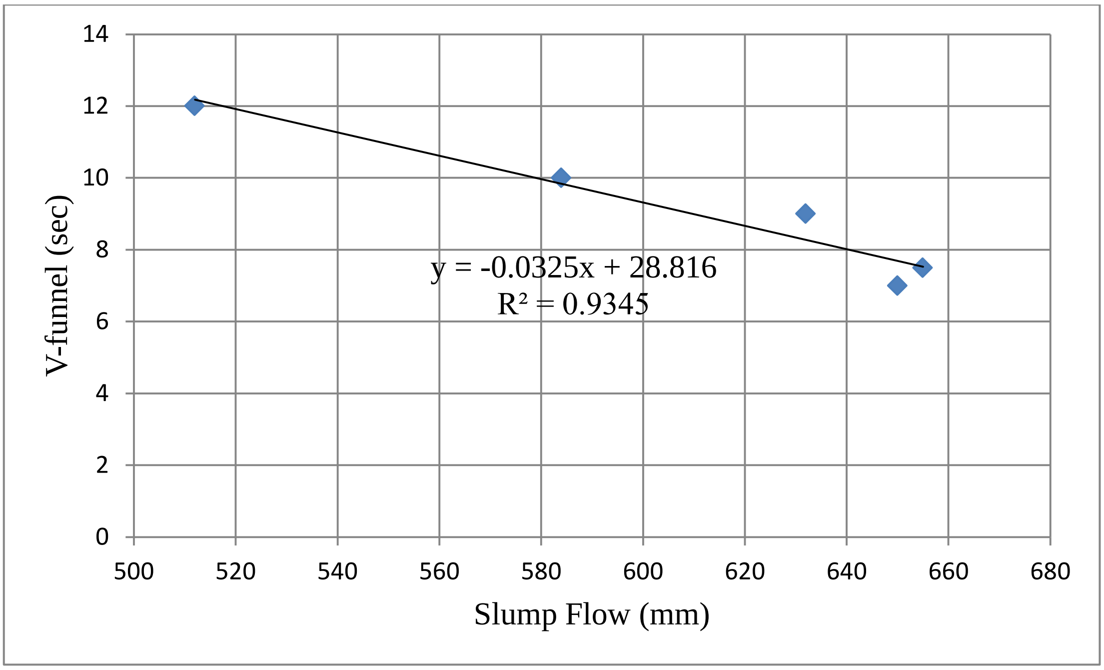


Figure 4.4: Linear Relationship between V-funnel and Slump Flow for WPET-SCC Concrete

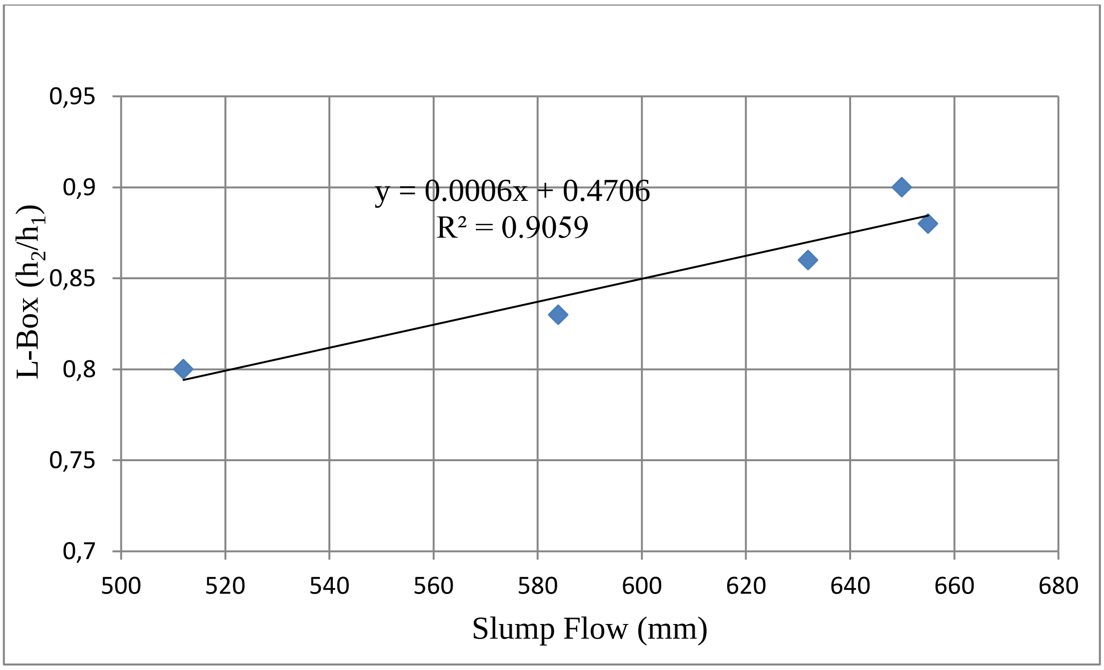


Figure 4.5: Linear Relationship between L-Box and Slump Flow for WPET-SCC Concrete

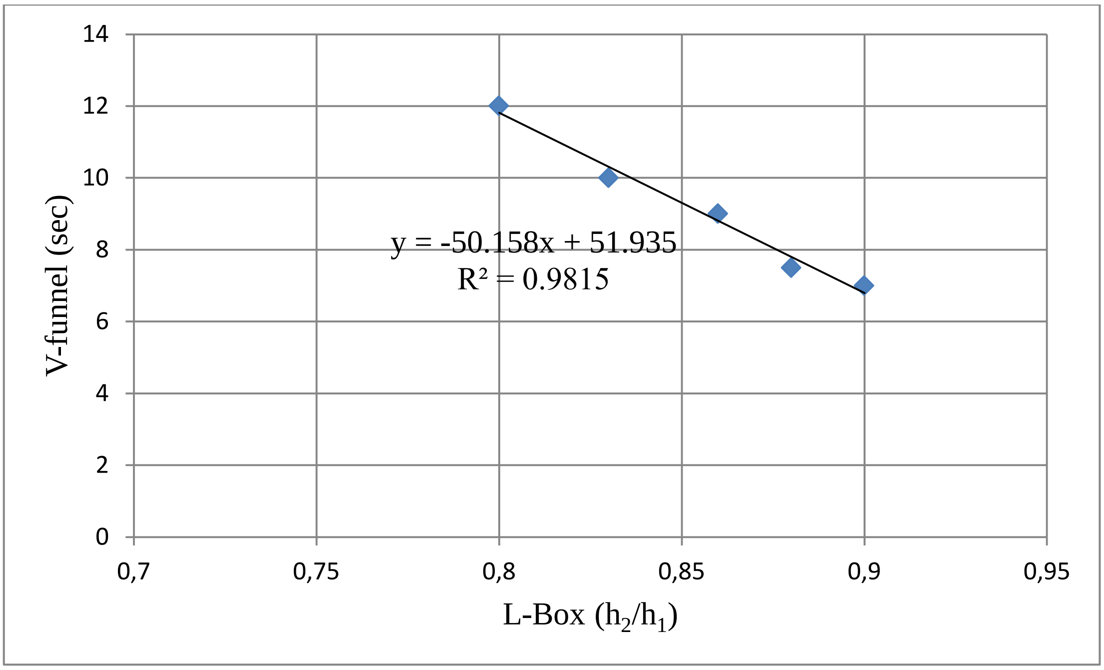


Figure 4.6: Linear Relationship between V-funnel and L-Box for WPET-SCC Concrete

Table 4.2: Linear Relationship between Different Types of Workability Tests

| Relationship Type | Regression Type | Equation | $R^2$ |
|---|---|---|---|
| V-funnel - Slump Flow | Linear | y = -0.0325x + 28.816 | 0.9345 |
| L-Box - Slump Flow | Linear | y = 0.0006x + 0.4706 | 0.9059 |
| V-funnel - L-Box | Linear | y = -50.158x + 51.935 | 0.9815 |

## 4.3 Hardened Concrete Tests

### 4.3.1 Compressive Strength ($\sigma_c$) of WPET-SCC Concrete

Generally, the use of waste PET as aggregates weakens the strength of WPET-SCC mixtures significantly. In order to investigate the effect of waste PET as a partial replacement with crushed coarse aggregate on $\sigma_c$, three cubes of size 150x150x150 mm were tested for obtaining the average test result at 28 days. The $\sigma_c$ test results for the five different concrete mixes (Control, M1, M2, M3 and M4) are shown in Table 4.3 and Figure 4.7.

As it can be seen from Table 4.3 and Figure 4.7, the $\sigma_c$ at 28 days of M1, M2, M3, and M4 specimens is reduced by 13.08, 22.97, 31.81 and 38.28 %, respectively compared with control specimens, so does the density when its loss reached 8.23 % when the WPET content was 20 %. On the one hand, the specific surface area of PET aggregates is greater than the conventional coarse aggregate because of their flat form, which augments the water content in the transition interfacial zone, as a result, this zone will increase. Therefore, the microstructures of concrete will be weak because of the increasing of the porosity in this zone, which lead to a reduction in σc. On the other hand, this reduction could be caused by the limit hydration of cement in concrete mixes due to the hydrophobic nature of PET which prevents the water penetration in the concrete structure. In addition, when the coarse aggregates are replaced with WPET, the stress transfer between cement matrix and coarse aggregate will be poorer.

Table 4.3: 28 – Days Compressive Strength of WPET-SCC Concrete Test Results

| Mixture Type | $\sigma_c$ (MPa) | Change in $\sigma_c$ (%) | Density ($Kg/m^3$) | Change in Density (%) |
|---|---|---|---|---|
| Control (0%) | 59.63 | - | 2343 | - |
| M1 (5%) | 51.83 | -13.08 | 2340 | -0.12 |
| M2 (10%) | 45.93 | -22.97 | 2300 | -1.83 |
| M3 (15%) | 40.66 | -31.81 | 2240 | -4.39 |
| M4 (20%) | 36.8 | -38.28 | 2150 | -8.23 |

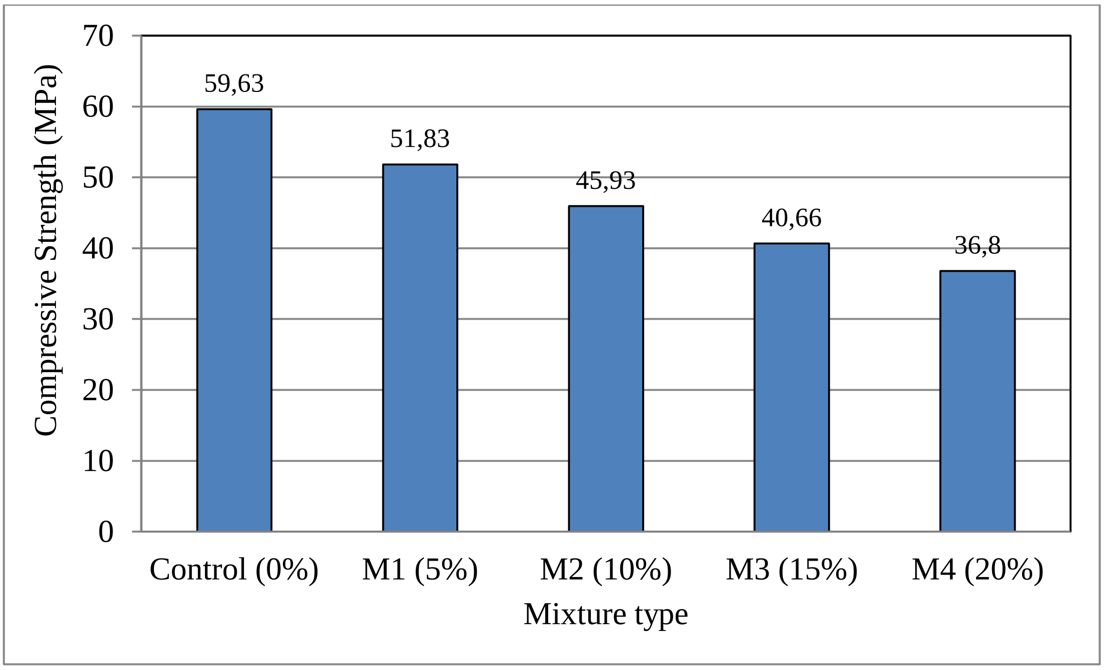


Figure 4.7: Compressive Strength Test Results for WPET-SCC Concrete

### 4.3.2 Splitting Tensile Strength ($\sigma_s$) of WPET-SCC Concrete

Figure 4.8 illustrates the splitting tensile strength changes of specimens after 28 days. Obviously, the $\sigma_s$ of samples has been decreased when PET aggregates were incorporated in SCC mixtures. The $\sigma_s$ of mixes M1, M2, M3, and M4 has been reduced about 13.08, 22.97, 38.28, and 31.81 % respectively compared with control SCC mixture, when PET replacement percentage was increased from 5 to 20 %.

This $\sigma_s$ reduction is owing to the negative behavior of PET particles that increase brittleness of the concrete specimens. In addition, the $\sigma_s$ of the concrete samples really depends on the interfacial transition zone (ITZ) between aggregates and cement paste, the stronger is the ITZ, the higher is the $\sigma_s$. As the replacement of coarse aggregates with waste PET particles weakens the ITZ of the concrete, the $\sigma_s$ reduces with increasing percentage of replacement.

Table 4.4: Splitting Tensile Strength of WPET-SCC Concrete Test Results

| Mixture Type | $\sigma_s$ after 28 days (MPa) | Change in $\sigma_s$ (%) |
|---|---|---|
| Control (0%) | 4.995 | - |
| M1 (5%) | 4.564 | -8.628 |
| M2 (10%) | 4.36 | -12.71 |
| M3 (15%) | 4.045 | -19 |
| M4 (20%) | 3.995 | -20.02 |

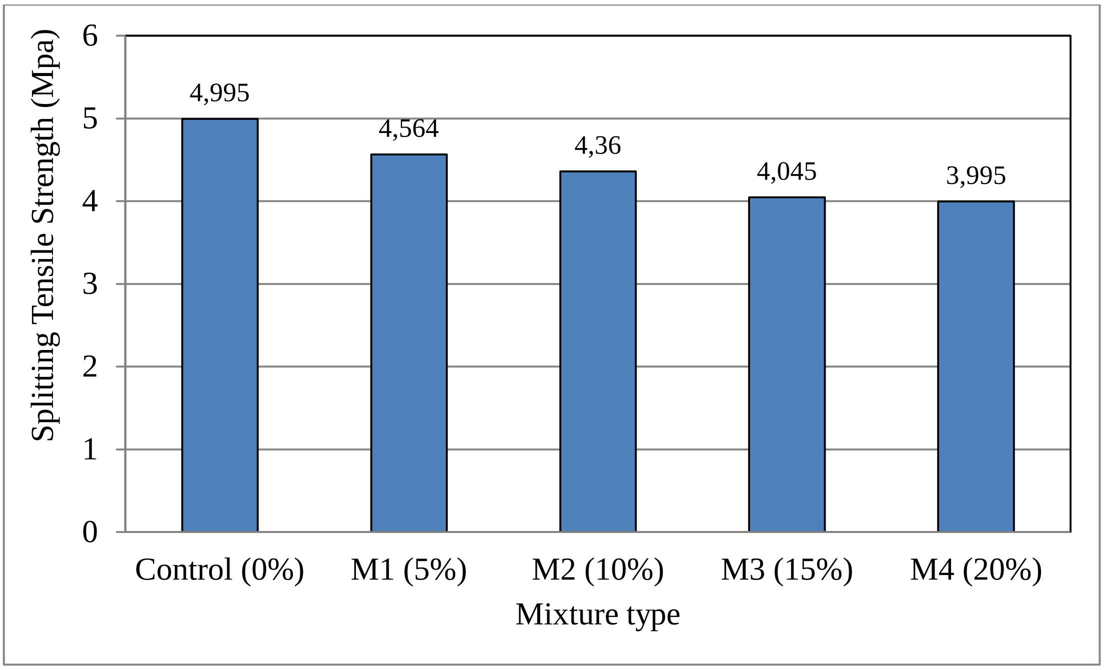


Figure 4.8: Splitting Tensile Strength Test Results for WPET-SCC Concrete

In order to see the best relationship between $\sigma_s$ and $\sigma_c$, the regression coefficient $R^2$ was calculated for different regression types (Exponential, Linear, Logarithmic, Polynomial, and Power), the closer $R^2$ is to one, the less is the dispersion, and the highest value of $R^2$ was recorded to the polynomial type with $R^2$ of 0.991 as it is clarified in Table 4.5. However, for the sake of simplicity and better understanding, the linear relationship is adopted in this research.

Figure 4.9 shows the linear relationship between $\sigma_s$ and $\sigma_c$ for coarse aggregates replacement with waste PET at 28 days, this figure reveals that the increment of waste PET decreases both $\sigma_c$ and $\sigma_s$.

Table 4.5: Different Relationships between Splitting Tensile Strength and Compressive Strength of WPET-SCC Concrete

| Relation type | Regression Type | Equation | $R^2$ |
|---|---|---|---|
| | Exponential | $y = 2.7271e^{0.0101x}$ | 0.986 |

|  |  |  |  |
|---|---|---|---|
| $\sigma_s - \sigma_c$ | Linear | $y = 0.0449x + 2.2838$ | 0.9834 |
|  | Logarithmic | $y = 2.1068\ln(x) - 3.6872$ | 0.9668 |
|  | Polynomial | $y = 0.0006x^2 - 0.0083x + 3.5303$ | 0.9901 |
|  | Power | $y = 0.7111x^{0.4739}$ | 0.9736 |

X: Compressive strength Y: Splitting tensile strength

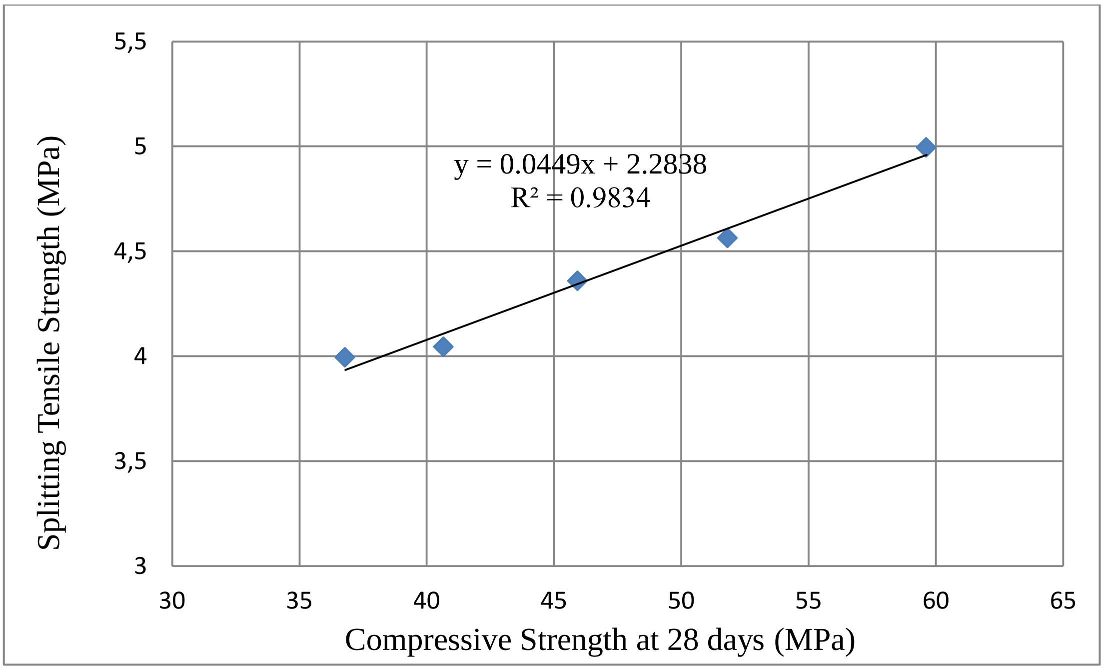


Figure 4.9: Linear Relationship between Splitting Tensile Strength and Compressive Strength for WPET-SCC Concrete

### 4.3.3 Ultrasonic Pulse Velocity Test (UPV) of WPET-SCC Concrete

High velocities are indicators of good quality of concrete, while low velocities signify a weak concrete contains too many cracks and voids. Concrete is considered as excellent if its velocity is greater than 4 km/sec, and it is considered as very good if its velocity is between 3.5-4 km/sec, and if concrete velocity is between 3-3.5 km/sec it is considered good, but if concrete velocity is less than 3 km/sec it is considered as weak concrete (Whitehurst, 1951).

Based on Table 4.6, the velocities of all concrete specimens are higher than 4 km/sec and the concrete in all samples is considered a high quality concrete.

Figure 4.10 shows that the velocity of concrete samples decreased gradually as the plastic content in the mixes increased, this loss reached 17.42 % when the percentage of replacement is 20 %, this is because adding waste PET particles improves the porosity of concrete by the cavities and pores that formed, so the ultrasonic wave takes more time to propagate through the inhomogeneous concrete sample.

Table 4.6: UPV Test Results

| Mixture Type | Time (μsec) | Pulse Velocity (km/sec) | Quality of Concrete | Changes Compared to Control (%) |
|---|---|---|---|---|
| Control (0%) | 20.75 | 4.82 | Excellent | - |
| M1 (5%) | 22.7 | 4.4 | Excellent | -8.71 |
| M2 (10%) | 23.95 | 4.17 | Excellent | -13.48 |
| M3 (15%) | 24.7 | 4.04 | Excellent | -16.18 |
| M4 (20%) | 25 | 4 | Excellent | -17.42 |

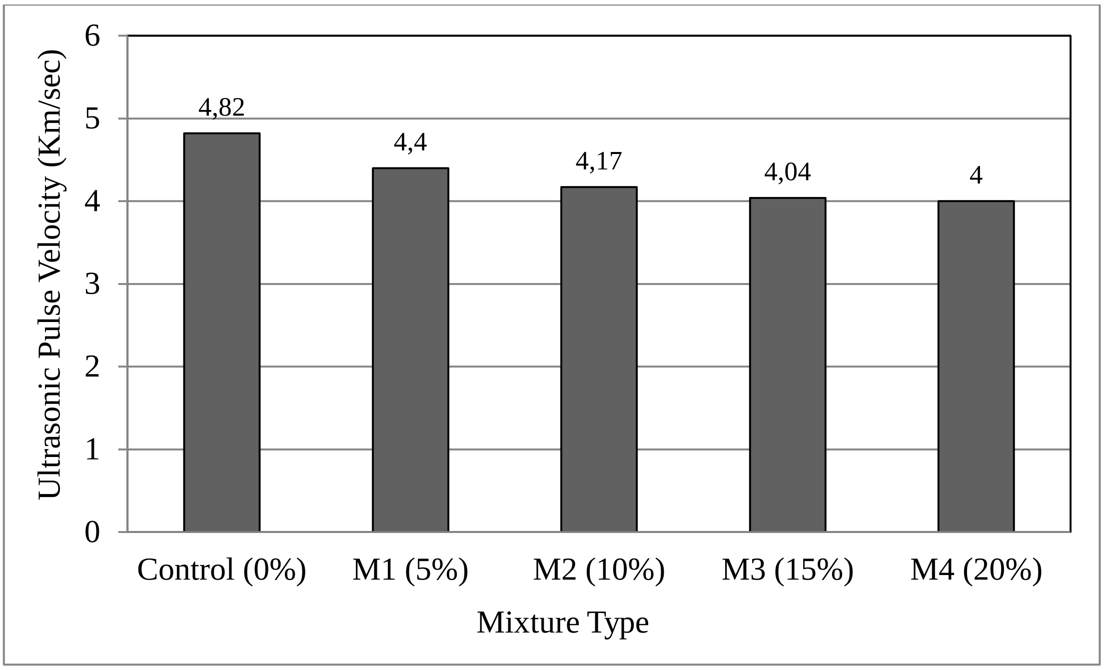


Figure 4.10: UPV Test Results

### 4.3.4 Flexural Toughness Test of WPET-SCC Concrete

On the one hand, Table 4.7 shows that the inclusion of PET particles in concrete reduced the $\sigma_f$ of the samples compared to the reference specially at high percentages of PET, when the $\sigma_f$ of concrete decreased from 11.49 (control) to reach 7.58 MPa at 20 % substitution level of coarse aggregate with PET. This is due to the accumulation of PET particles next to each other which reduces the cement-PET cohesion and leads to strength loss.

On the other hand, raising the PET content gave concrete samples more flexibility and deformation before rupture; this can be noticed from the areas under the curves when it seems to increase as the PET content increases to reach its maximum at 20 % replacement of PET when the curve shows more flexibility and more extension than the other curves (see Figures 4.11, 4.12, 4.13, 4.14, 4.15). This may because the flexibility of plastic particles is higher than the conventional coarse aggregate, and the flat shape of PET particles that has a tendency to locate perpendicularly in the direction of applied load, in a result, the elasticity modulus of WPET-SCC decreased and the concrete become more deformable.

Table 4.7: Maximum Loads and Flexural Strength Test Results of Beams

| Mixture Type | Maximum Load (KN) | $\sigma_f$ (MPa) | Changes (%) |
|---|---|---|---|
| Control | 12.77 | 11.49 | - |
| M1 (5%) | 12.33 | 11.09 | -3.48 |
| M2 (10%) | 11.42 | 10.27 | -10.61 |
| M3 (15%) | 10.18 | 9.162 | -20.26 |
| M4 (20%) | 8.427 | 7.58 | -34.02 |

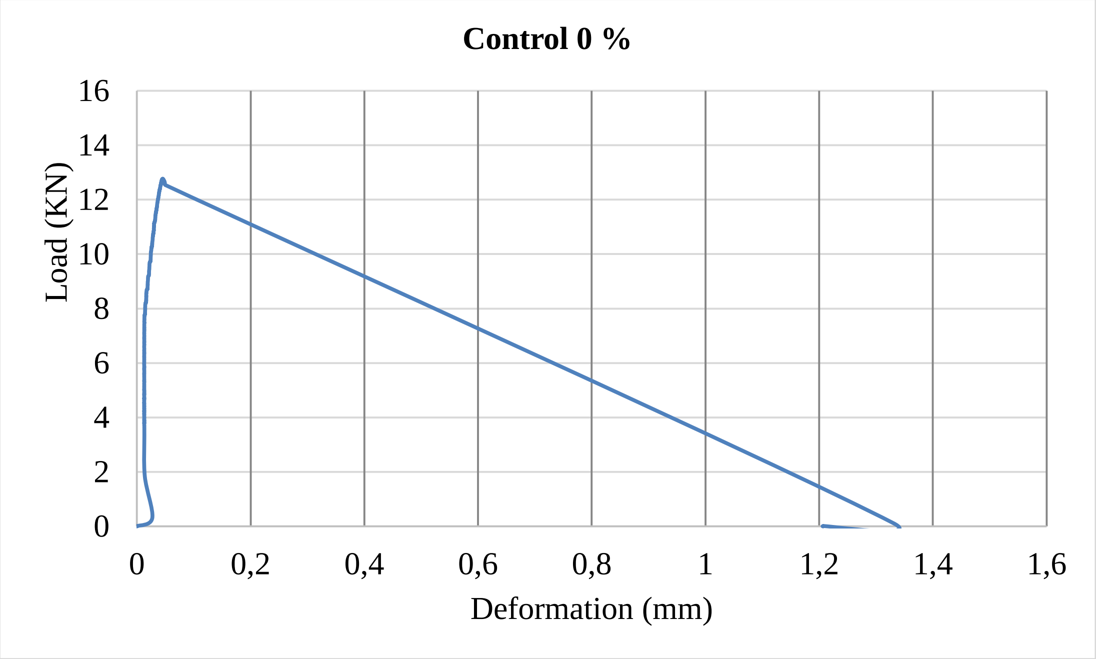


Figure 4.11: Flexural Toughness Test Result for Control Specimen

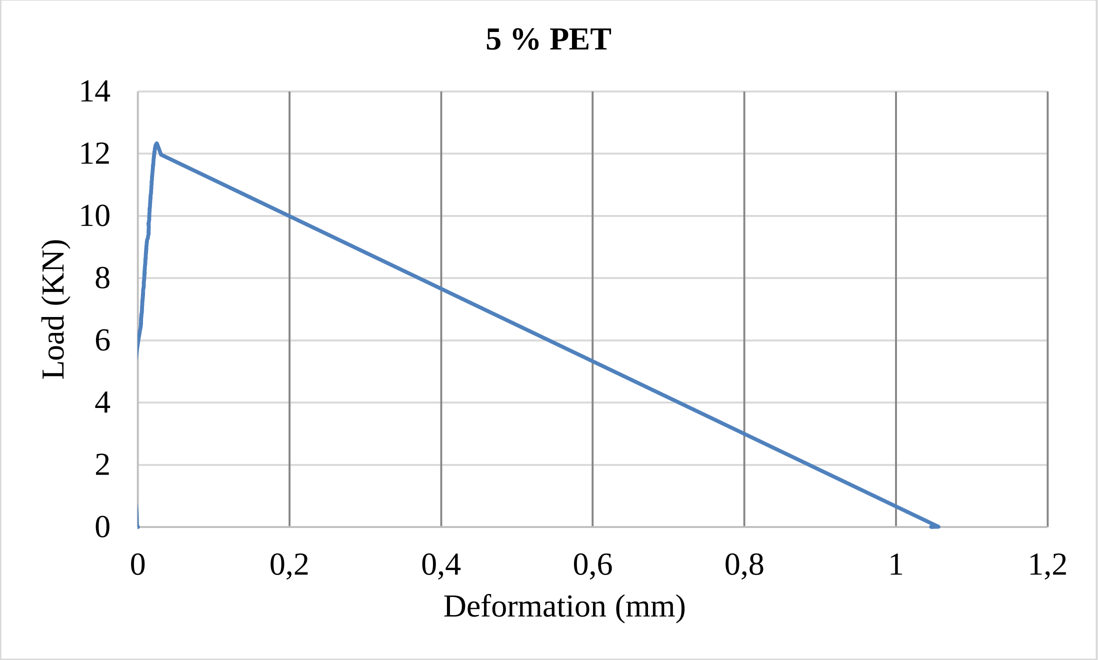


Figure 4.12: Flexural Toughness Test Result for specimen with 5 % WPET

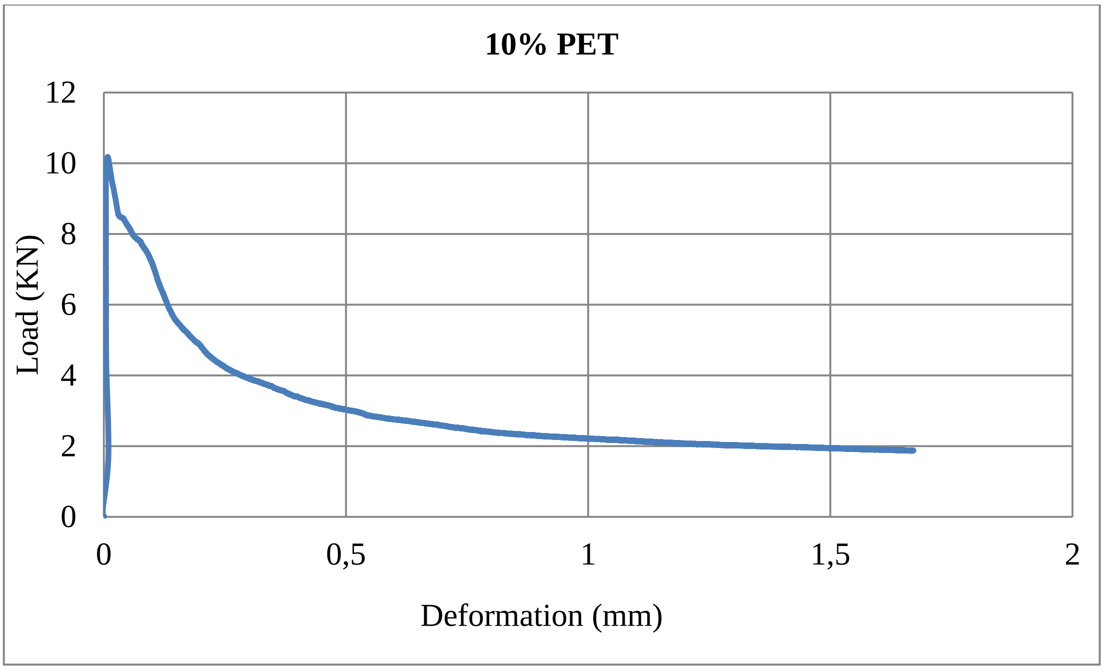


Figure 4.13: Flexural Toughness Test Result for specimen with 10 % WPET

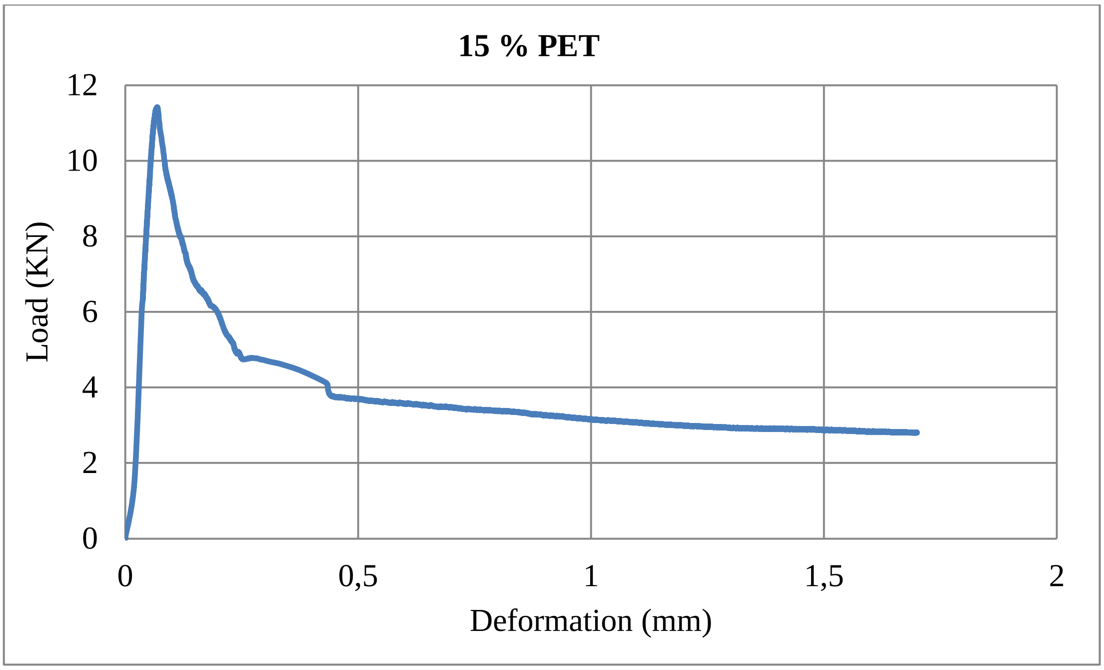


Figure 4.14: Flexural Toughness Test Result for specimen with 15 % WPET

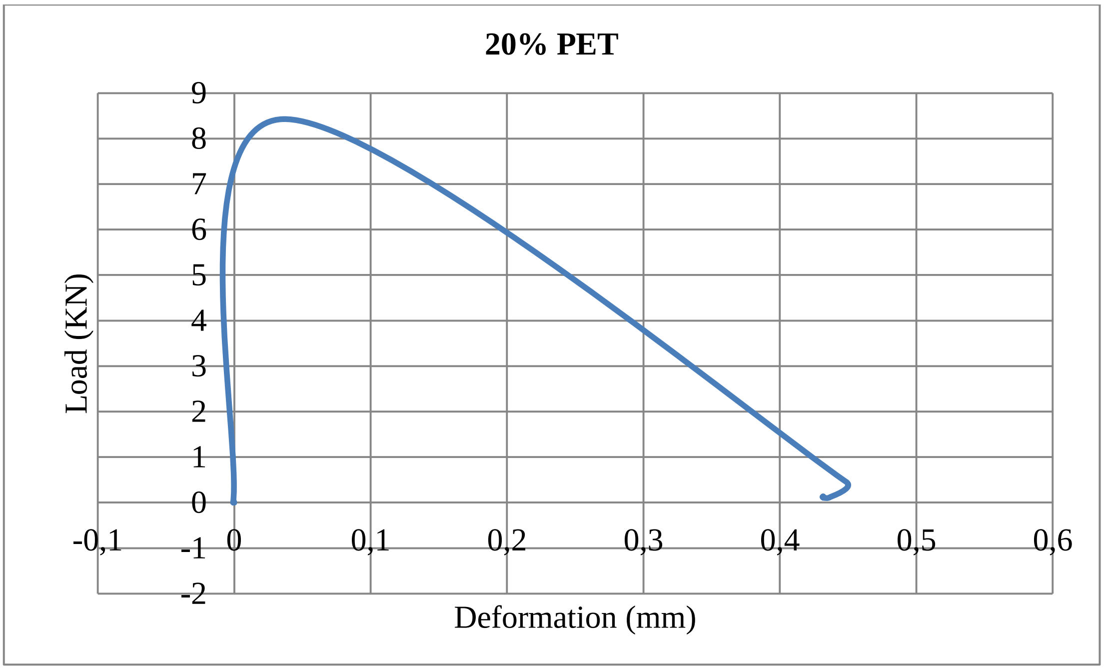


Figure 4.15: Flexural Toughness Test Result for specimen with 20 % WPET

In addition, $R^2$ for different regression types was calculated in order to see the best relationship between $\sigma_s$ and $\sigma_c$, the closer $R^2$ is to one, the less is the dispersion. $R^2$ recorded the closest value to 1 for the polynomial type with 0.9938 as it is shown in

Table 4.8. However, the linear relationship is chosen in this research for the aim of simplicity.

Figure 4.16 shows the linear relationship between compressive strength and flexural strength for coarse aggregates replacement with waste PET at 28 days, this figure shows that the increment of waste PET decreases both compressive strength and flexural toughness.

Table 4.8: Different Relationships between Flexural Strength and Compressive Strength of WPET-SCC Concrete

| Relationship | Regression | Equation | $R^2$ |
|---|---|---|---|
| $\sigma_f$ - $\sigma_c$ | Exponential | $y = 4.3999e^{0.0171x}$ | 0.8443 |
| | Linear | $y = 0.1639x + 2.2224$ | 0.8806 |
| | Logarithmic | $y = 7.9378\ln(x) - 20.522$ | 0.9220 |
| | Polynomial | $y = -0.0087x^2 + 1.0068x - 17.527$ | 0.9938 |
| | Power | $y = 0.4064x^{0.8302}$ | 0.8908 |

X: Compressive Strength Y: Flexural Strength

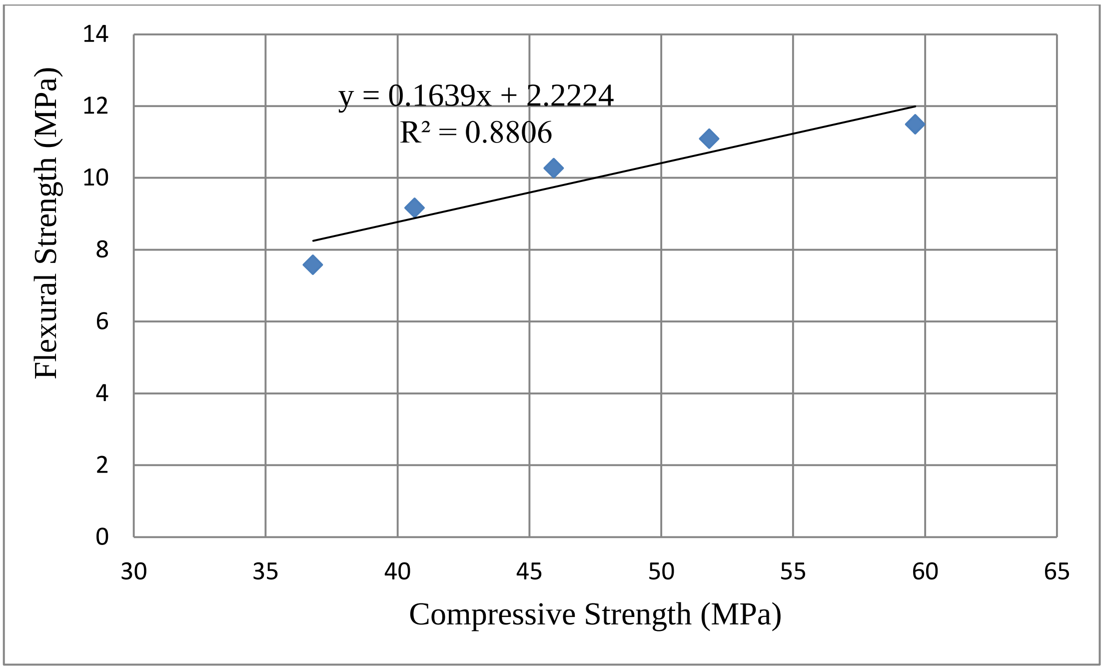


Figure 4.16: Linear Relationship between Flexural Strength and Compressive Strength for WPET-SCC Concrete

### 4.3.5 Resistance of WPET-SCC to Heat Exposure

With the intention of studying the influence of temperature on the physical and mechanical properties and the morphology of self-compacted concrete, $\sigma_c$, $\sigma_s$, UPV, weight, and the changes presented on the surface are examined after exposing concrete cubic samples (100×100×100 mm) to two different temperatures.

Regarding the samples exposed to 100 °C, no significant variations were noticed in the mechanical properties of concrete when compared to the unheated samples. The loss in $\sigma_c$ was 10.8, 10.7, 1.84, 6.06, and 7.21 % for control, M1, M2, M3, and M4 respectively (see Table 4.9), for splitting tensile strength, UPV, and weight, this loss reached 5.18, 6.64 and 2.32 % respectively (see Table 4.11 and 4.12).

In concrete mixes exposed to 200 °C, the variations in mechanical properties of concrete increased and became more serious when the loss of $\sigma_c$ reached 25.11 %

for M3 (see Table 4.9). For the $\sigma_s$, weight, and UPV, this loss reached -20.9, 9.37, and 17.01 % respectively compared to the unexposed samples (see Table 4.10, 4.11, and 4.12).

This loss in mechanical and physical properties of SCC is because the chemical reactions that occurred among the ingredients of concrete mixture, and the degradation of plastic particles. Besides, this may due to the shrinkage that occurred because of the loss of water caused by the high temperatures, that lead to a volume change of 0.5 % (Albano et al, 2009), also the thermodegradative behavior of PET is one of the reasons that affect concrete and lead to less cohesion between the components of concrete and produce a greater number of voids. In addition, at high temperatures, when water evaporates, the discharging of vapor is difficult, which creates a pressure on the concrete and support voids and cracks formation on concrete; as a result, concrete properties are affected.

Concerning the concrete morphology, a Stereo-microscope was used in order to detect the cracks development on concrete surfaces after exposing it to 100 and 200 °C temperatures, and to measure the width of the biggest crack. At both 100 and 200 °C, Figures 4.21, 4.22, and 4.23 show the surfaces of control, M1, M2, M3 and M4 respectively, before and after exposing them to 100 and 200 °C temperatures. As it is cleared, no cracks were detected on the surfaces, as well as no change in color was noticed. Thus, it can be concluded that at 100 and 200 °C, the WPET-SCC mixes are able to resist the chemical reactions that occurred. However, at 200 °C a change in PET particles color and properties was noticed, when their color changed from white and transparent to blue and dark as shown in the Figure 4.23f, as well as their ductility decreased and they became more brittle.

Besides, the linear relationships between $\sigma_s$- $\sigma_c$, $\sigma_c$-UPV, and $\sigma_s$-UPV were plotted before and after exposing the specimens to 100 and 200 °C temperatures as illustrated in Figures 4.24, 4.25, and 4.26. These figures show that the $\sigma_s$, the σc and the UPV, are all proportional, they increase and decrease together. Moreover, $R^2$ for different relationships type was calculated at all 3 different temperatures, in order to see the effect of temperature on the dispersion of points, the closer $R^2$ is to one, the less the dispersion. It can be noticed from Figures 4.24, 4.25, and 4.26 and Tables 4.13, 4.14, and 4.15, that as the temperature increased, $R^2$ became farther to one and the dispersion of points increased, especially at high temperature (200 °C), when $R^2$ decreased from 0.9758 to reach 0.272 for $\sigma_s$-UPV relationship (see Table 4.14).

Table 4.9: Compressive Strength Test Results before and after Exposure to Heat at 100 and 200 °C

| Mixture type | $\sigma_c$ before heating (MPa) | $\sigma_c$ after 100 °C heating (MPa) | Loss in $\sigma_c$ (%) | $\sigma_c$ after 200 °C heating (MPa) | Loss in $\sigma_c$ (%) |
|---|---|---|---|---|---|
| control | 75.5 | 67.35 | -10.8 | 61.3 | -18.8 |
| M1 (5%) | 60.63 | 54.1 | -10.7 | 50.45 | -16.79 |
| M2 (10%) | 58.43 | 57.35 | -1.84 | 48.43 | -17.11 |
| M3 (15%) | 48.6 | 45.65 | -6.06 | 36.4 | -25.11 |
| M4 (20%) | 47.53 | 44.1 | -7.21 | 42.2 | -11.21 |

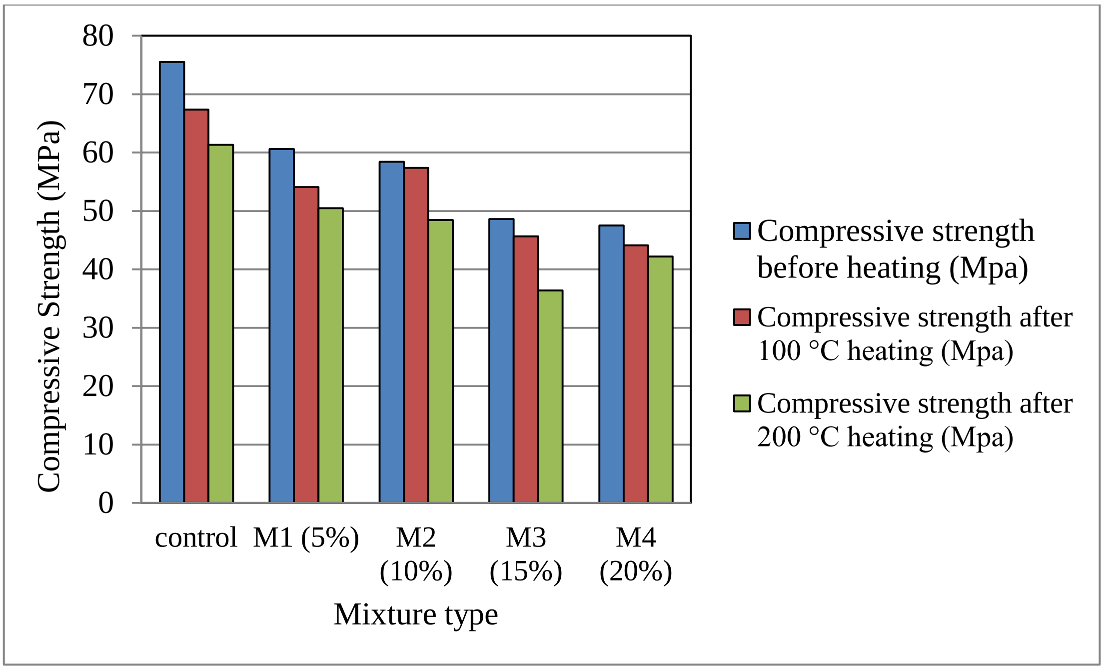


Figure 4.17: Compressive Strength Test Results before and after Exposure to Heat at 100 and 200 °C

Table 4.10: Splitting Tensile Strength before and after Exposure to Heat at 100 and 200 °C

| Mixture type | $\sigma_s$ before heating (MPa) | $\sigma_s$ after 100 °C heating (MPa) | Loss in $\sigma_s$ (%) | $\sigma_s$ after 200 °C heating (MPa) | Loss in $\sigma_s$ (%) |
|---|---|---|---|---|---|
| Control | 4.34 | 4.25 | -2.07 | 3.79 | -12.67 |
| M1 (5%) | 3.96 | 3.95 | -0.25 | 3.59 | -9.34 |
| M2 (10%) | 3.78 | 3.72 | -1.58 | 2.99 | -20.9 |
| M3 (15%) | 3.53 | 3.52 | -0.28 | 3.22 | -8.78 |
| M4 (20%) | 3.47 | 3.29 | -5.18 | 3.035 | -12.53 |

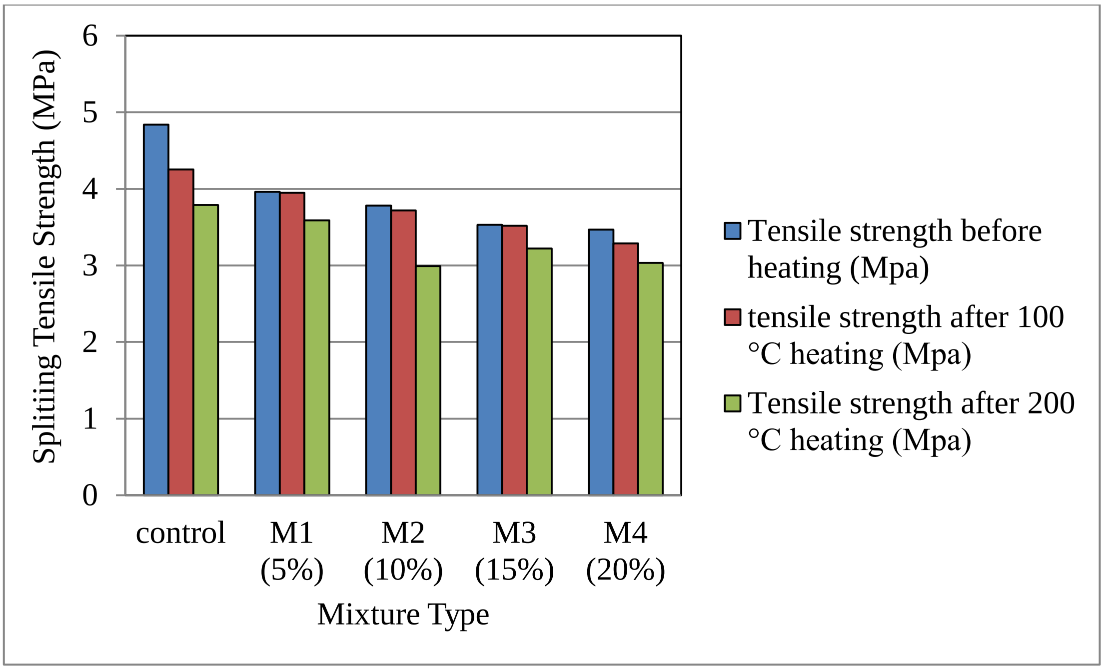


Figure 4.18: Splitting Tensile Strength Test Results before and after Exposure to Heat at 100 and 200 °C

Table 4.11: UPV Test Results before and after Exposure to Heat at 100 and 200 °C

| Mixture type | Velocity before heating (km/sec) | Velocity after 100 °C heating (km/sec) | Loss in UPV (%) | Velocity after 200 °C heating (km/sec) | Loss in UPV (%) |
|---|---|---|---|---|---|
| Control (0%) | 4.82 | 4.5 | -6.64 | 4 | -17.01 |
| M1 (5%) | 4.4 | 4.28 | -2.72 | 4.2 | -4.54 |
| M2 (10%) | 4.17 | 4.14 | -0.72 | 4.03 | -3.35 |
| M3 (15%) | 4.04 | 4 | -1 | 3.55 | -12.12 |
| M4 (20%) | 4 | 3.75 | -6.25 | 3.57 | -10.75 |

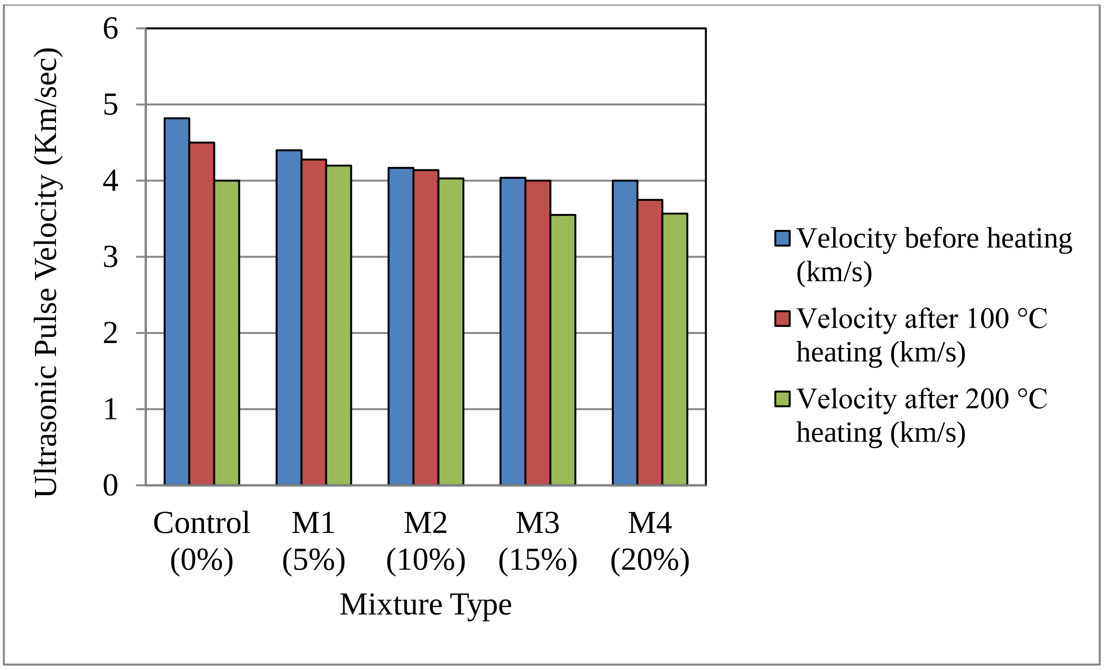


Figure 4.19: UPV Results before and after Exposure to Heat at 100 and 200 °C

Table 4.12: Specimens Weight before and after Exposure to Heat at 100 and 200 °C

| Mixture type | Weight before heating (kg) | Weight after 100 °C heating (kg) | Loss in weight (%) | Weight after 200 °C heating (kg) | Loss in weight (%) |
|---|---|---|---|---|---|
| Control (0%) | 2.343 | 2.32 | -0.98 | 2.16 | -7.81 |
| M1 (5%) | 2.34 | 2.32 | -0.85 | 2.13 | -8.97 |
| M2 (10%) | 2.3 | 2.29 | -0.43 | 2.11 | -8.26 |
| M3 (15%) | 2.15 | 2.1 | -2.32 | 2.02 | -6.04 |
| M4 (20%) | 2.24 | 2.21 | -1.34 | 2.03 | -9.37 |

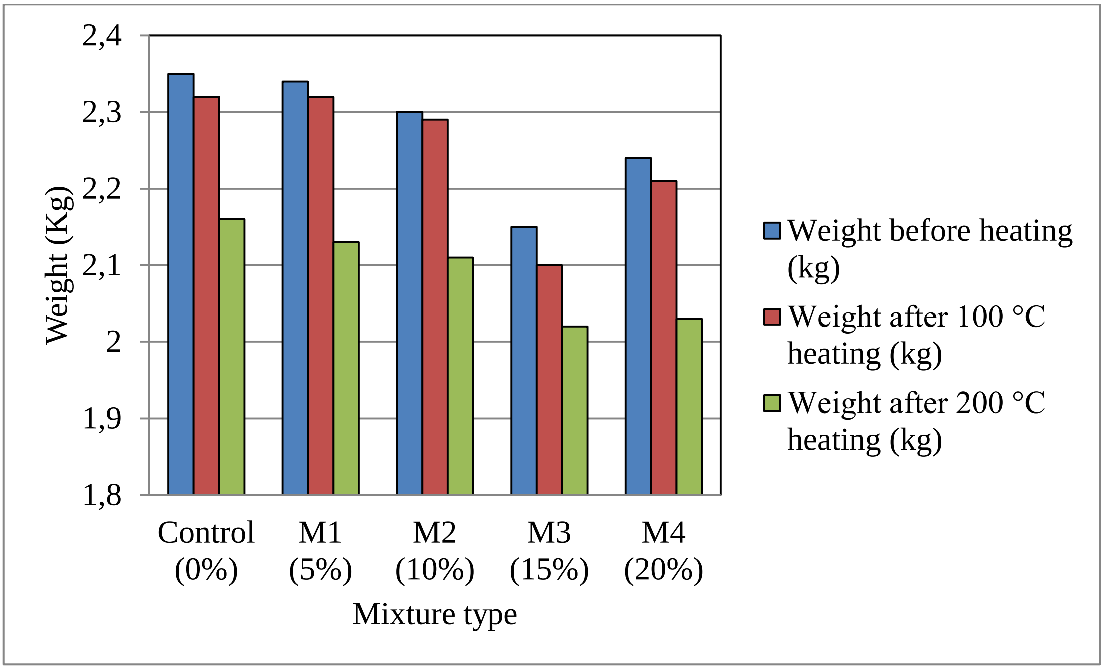
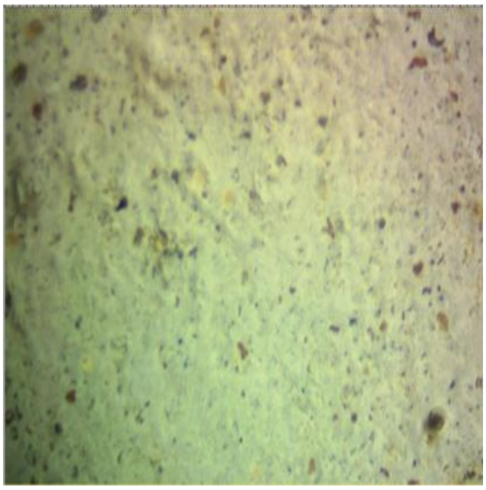
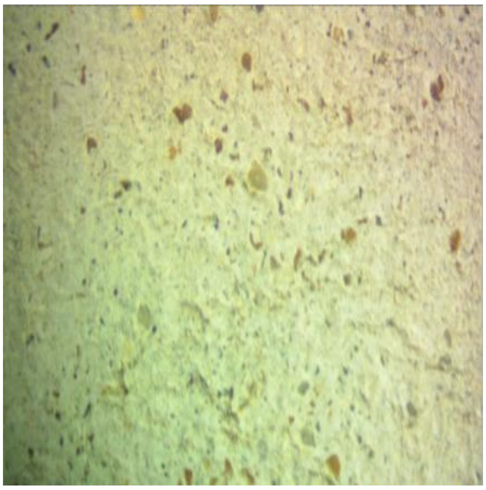


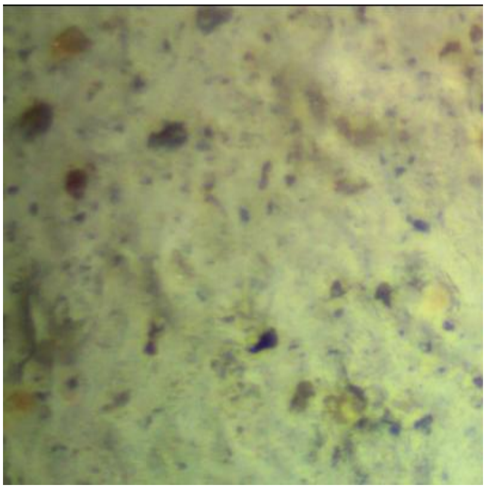
Figure 4.20: Specimens Weight before and after Exposure to Heat at 100 and 200 °C



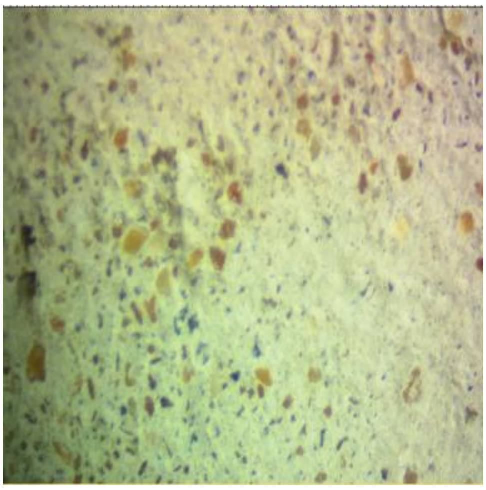
a) Control



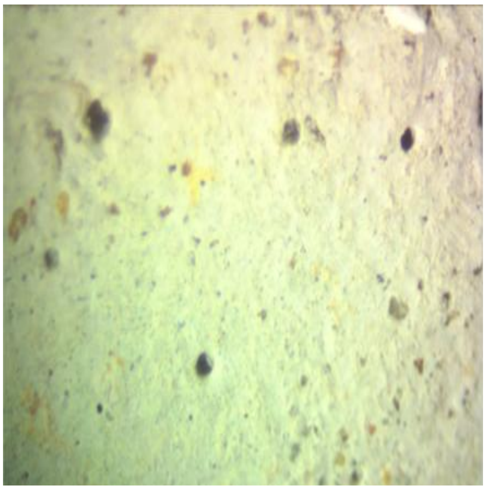
b) M1



c) M2

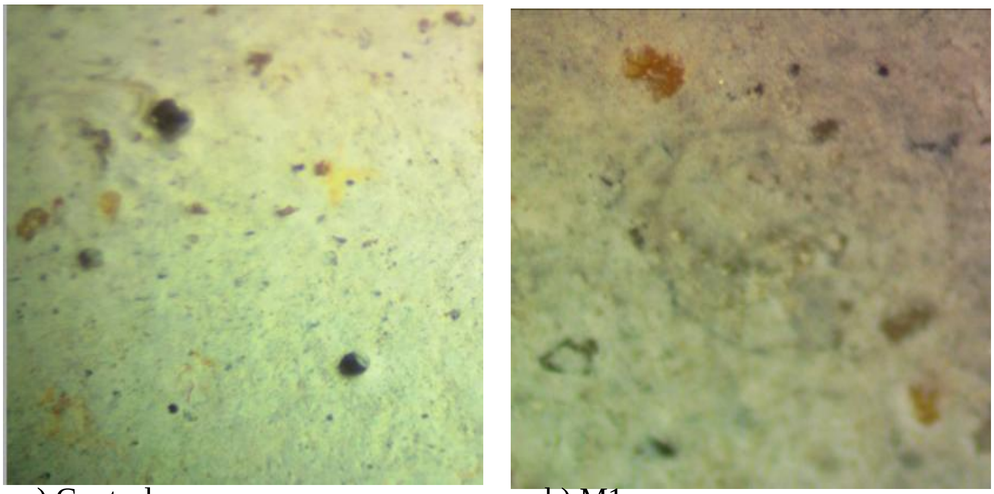


d) M3

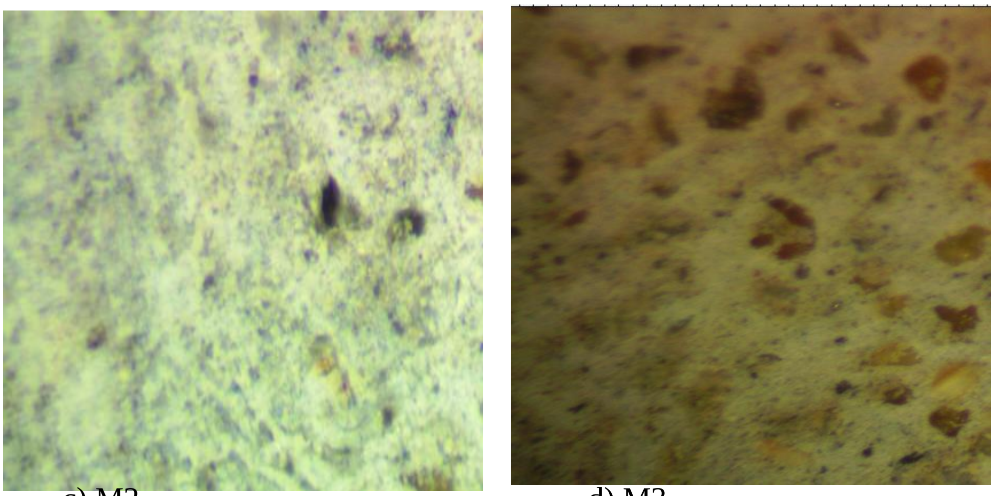


e) M4

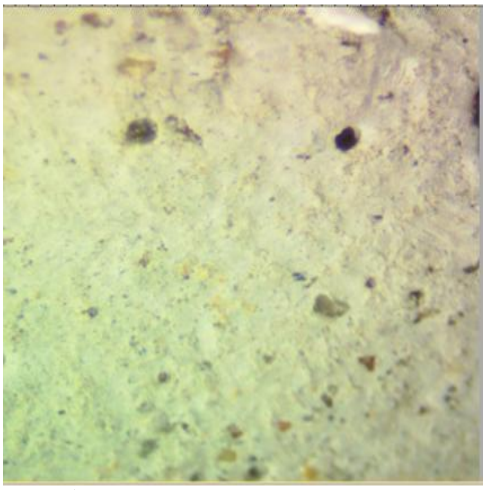
Figure 4.21: WPET-SCC Surfaces before Exposing to Heat



a) Control b) M1

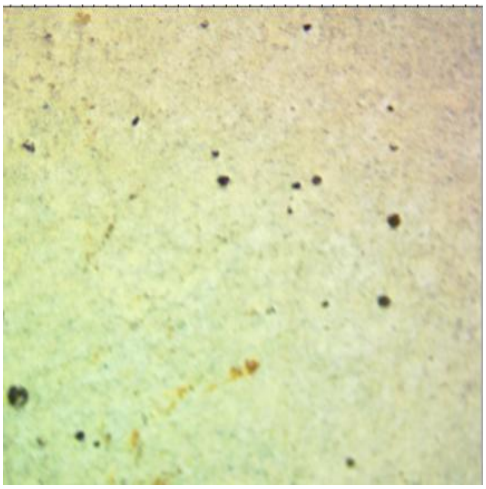


c) M2 d) M3



e) M4

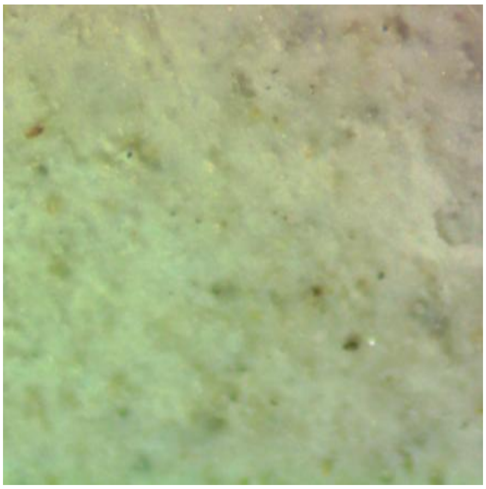
Figure 4.22: WPET-SCC Surfaces after Exposure to Heat at 100 °C



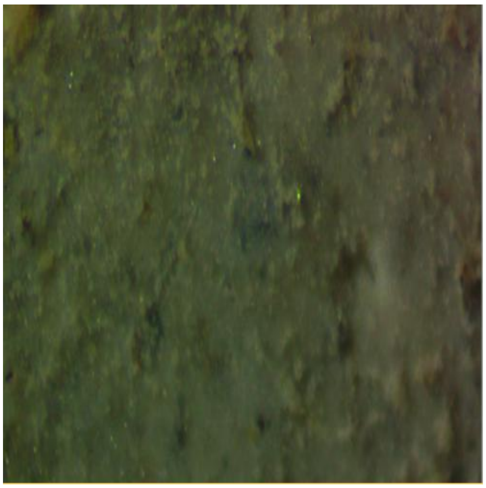
a) Control

b) M1

c) M2



d) M3



e) M4

f) WPET

Figure 4.23: WPET-SCC Surfaces after Exposure to Heat at 200 °C

Table 4.13: Linear Relationship between Splitting Tensile Strength and Compressive Strength before and after Exposure to Heat at 100 and 200 °C for WPET-SCC Concrete

| Relationship Type | Temperature | Regression Type | Equation | $R^2$ |
|---|---|---|---|---|
| $\sigma_s$- $\sigma_c$ | Before Heat | Linear | y = 0.031x + 2.0142 | 0.9858 |
| | After 100 °C | Linear | y = 0.0366x + 1.7794 | 0.8613 |
| | After 200 °C | Linear | y = 0.0273x + 2.0202 | 0.5306 |

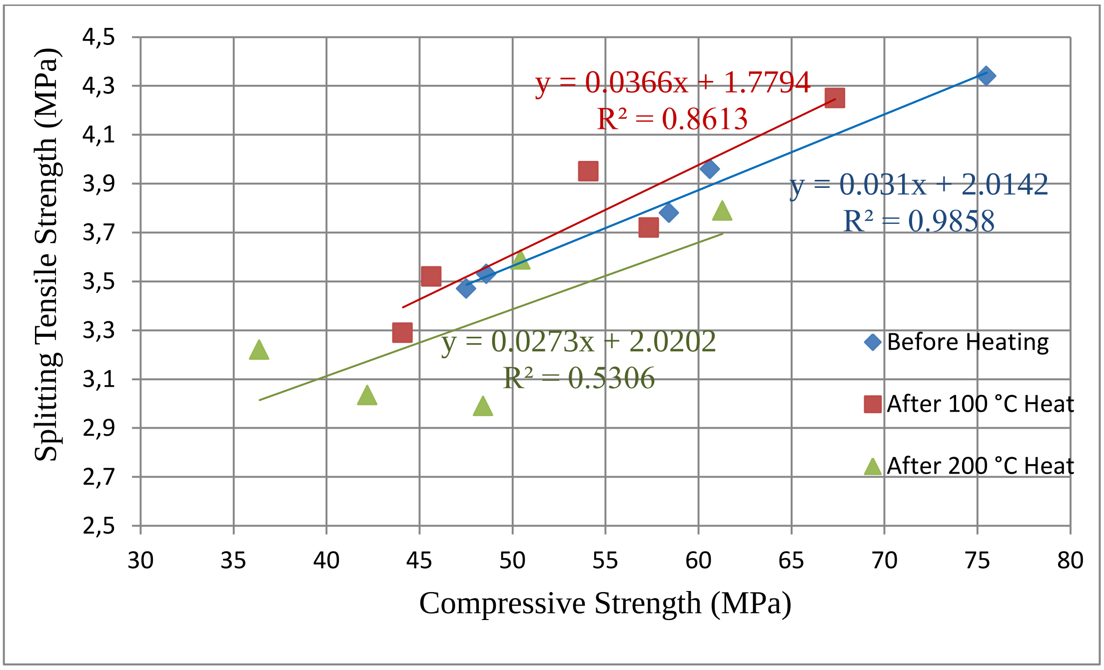


Figure 4.24: Linear Relationship between Splitting Tensile Strength and Compressive Strength before and after Exposure to Heat at 100 and 200 °C for WPET-SCC Concrete

Table 4.14: Linear Relationship between Splitting Strength and UPV before and after Exposure to Heat at 100 and 200 °C for WPET-SCC Concrete

| Relationship Type | Temperature | Regression Type | Equation | $R^2$ |
|---|---|---|---|---|
| $\sigma_s$-UPV | Before Heat | Linear | y = 1.0348x - 0.6192 | 0.9758 |
| | After 100 °C | Linear | y = 1.3079x - 1.661 | 0.988 |
| | After 200 °C | Linear | y = 0.6251x + 0.906 | 0.272 |

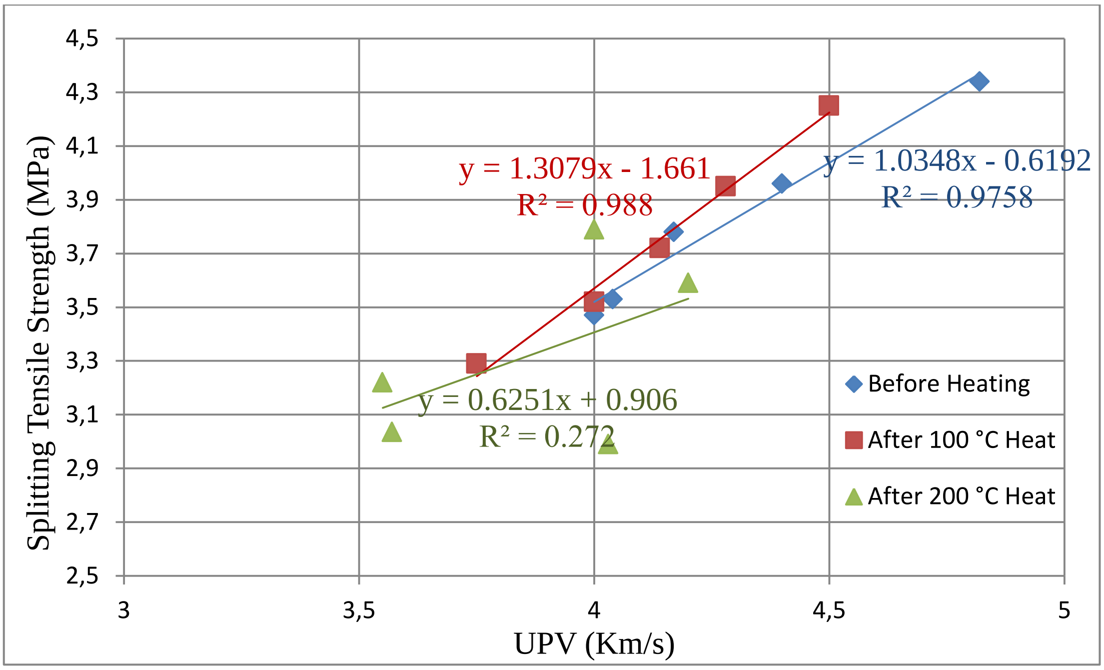


Figure 4.25: Linear Relationship between $\sigma_s$ and UPV before and after Exposure to Heat at 100 and 200 °C for WPET-SCC Concrete

Table 4.15: Relationship between Compressive Strength and UPV before and after Exposure to Heat at 100 and 200 °C WPET-SCC Concrete

| Relationship Type | Temperature | Regression Type | Equation | $R^2$ |
|---|---|---|---|---|
| $\sigma_c$-UPV | Before Heat | Linear | y = 32.829x - 82.567 | 0.9569 |
| | After 100 °C | Linear | y = 30.685x - 73.142 | 0.8464 |
| | After 200 °C | Linear | y = 23.439x - 42.953 | 0.5381 |

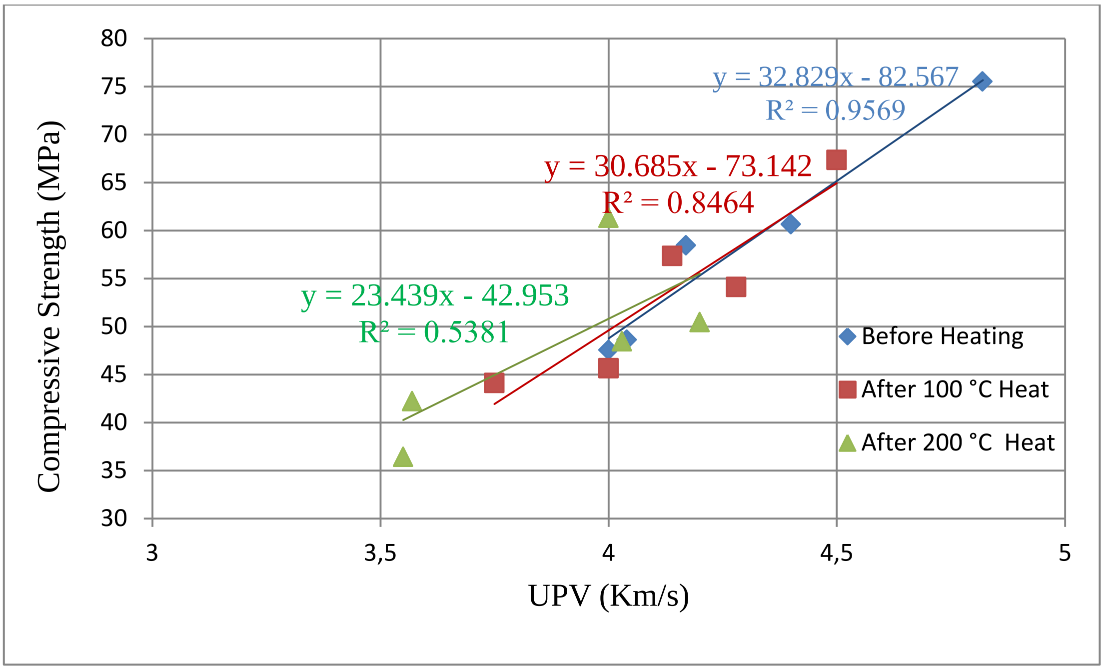


Figure 4.26: Linear Relationship between Compressive Strength and UPV before and after Exposure to Heat at 100 and 200 °C for WPET-SCC Concrete

# Chapter 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The influences of waste PET fragments on the mechanical, physical and durability properties of SCC were experimentally analyzed in this study. Accordingly, several conclusions have been made.

1. The incorporation of waste PET has negative effects on the mechanical, physical, and rheological properties of self-compacting concrete
2. The replacement of waste PET particles with the natural coarse aggregate affect the fresh WPET-SCC properties, when all the workability tests (L-box, V-funnel, Slump flow) indicate that the WPET-SCC workability in all mixes decreased as the PET content increased. However, up to 20 % replacement level of PET, it is possible to produce self-compacting concrete, since the workability requirements of SCC were achieved.
3. Waste PET fragments reduce the compressive and the $\sigma_f$ of WPET-SCC blends, owing to the flat and smooth shape of PET particles surface which decrease the cohesion between different components of concrete and PET particles. Beside, PET particles in high value tend to accumulate next to each other and lead to a weak cement-PET bonding, cause a loss in SCC strength.
4. The $\sigma_s$ decreases as the PET particles content increase, when the loss of strength reached 20.02 % compared to the control mix at 20 % replacement of PET particles with coarse aggregate.

5. As PET content in the concrete increase the UPV of samples decrease, because the high rate of voids and cracks that have been formed after PET addition.
6. Since PET particles are very ductile compared to the brittle conventional coarse aggregate, the addition of WPET creates a softening behavior to concrete which resulting an increase in ductility and toughness of WPET-SCC, and makes it more ductile.
7. The replacement of coarse aggregate with waste PET particles reduces the fresh and dry density of self-compacting concrete, causing weight reduction of created WPET-SCC, and provides the possibility of producing lightweight concrete.
8. The resistance against heat results of WPET-SCC mixtures are extremely depends on the temperature. At low temperature (100 °C) no remarkable variations are recorded, a slight decrease in $\sigma_c$, $\sigma_s$, UPV, and weight of the samples was observed, and no variations on the surface were observed. The serious changes were observed when the heating temperature was increased to 200 °C, the greatest loss was recorded for $\sigma_c$ when it reached 25.1 % for M3, and the degradation process of PET particles took place, that lead to less cohesion, and affect the mechanical and physical properties of concrete, without any detection of micro-cracks.

Generally, it is possible to use waste PET bottles as a replacement of coarse aggregate in self-compacting concrete, and reduce the dead loads (weight) of concrete to produce lightweight concrete, and protect the environment from these non-biodegradable materials by recycling them. Even though the substitution of the coarse aggregates by PET gives place to a decrease in mechanical properties, it can be used for encapsulating waste materials from other industries and to produce ecologically safe concretes, as well as sub-bases for highway pavements, highway medians and other transportation structures where high strength is not of prime importance. Finally, it is promising to use concrete-PET mixes within the construction field, in applications where high strength is not necessary.

## 5.2 Recommendations for Future Studies

1. Research the combined effect of waste PET particles as a partial replacement with sand and the glass powder as a partial replacement with cement on the physical, mechanical and rheological properties of concrete.
2. The influence of using waste PET particles on the mechanical behavior of fiber reinforced concrete
3. Investigating the combined effects of PET particles as a coarse aggregate replacement, and PET fibers as a concrete additive.
4. Studying the durability properties of WPET-SCC concrete such as water permeability, rapid chloride permeability, creep, plastic shrinkage and drying shrinkage, resistance to freezing and thawing, and degradation test at elevated temperatures.
5. Studying possibilities of increasing the strength of WPET-SCC concrete or compensating the strength loss when different replacement levels of WPET with coarse aggregate are incorporated in concrete. Such possibilities include reducing the w/c ratio and the use of superplasticizers and the use of different pozzolanic materials with WPET.

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