Effects of Waste Electronic Plastics and Marble Dust on Mechanical Behavior of High Strength Concrete

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ABSTRACT

The influence of utilizing waste electronic plastic (e-plastic) and waste marble dust (MD) on the mechanical and durability properties of high strength concrete (HSC) were investigated. For this purpose, concrete mixtures with a water to cement ratio of 0.40 were prepared. Shredded e-plastic waste was utilized as a partial replacement of natural aggregate at proportions of 0%, 10%, 20%, 30% and 40% by volume. In addition, MD was used as an additive by weight of cement at the proportions ranging from 0% to 15%. The unit weight, compressive, splitting tensile and flexural strength values, modulus of elasticity, stress-strain relationship under compression, load-deflection relation under flexure, toughness and permeability of the mixtures were determined. In addition, the impact of high temperatures (60ºC, 100ºC and 200ºC) on compressive strength and unit weight were determined and the obtained data were compared with the corresponding untreated specimens. Additionally, specimens were exposed up to the temperature of 300ºC to observe the temperature effect on the surface condition of concrete. Observed data indicated that the strength values, elastic modulus and unit weight of the test mixtures were lower than those of the control concrete. Furthermore, the least reduction in compressive strength, flexural strength and toughness occurred at 20% e-plastic replacement level. The tensile strengths, elastic modulus and unit weight were inversely proportional to the increment in the e-plastic content. On the other hand, the change in temperature resulted in the compressive strength loss up to 200ºC. Color changes were also observed on the concrete surfaces at 300ºC. TGA analysis of e-plastic particles also showed that weight losses became more pronounced at 300ºC compared to the

200ºC. Ultimately, the addition of MD slightly enhanced the properties and performance of the concrete.

Keywords: e-plastic waste, marble dust, high strength concrete, mechanical properties, permeability, toughness, durability.

ÖZ

Bu çalışmada, atık elektronik plastik (e-plastik) ve atık mermer tozunun yüksek dayanımlı betonun dayanım ve dayanıklılığına olan etkileri araştırıldı. Bu amaçla su/çimento oranı 0.40 olan beton karışımları hazırlandı. Elektronik plastikler agregaların yerine hacimce %0, %10, %20, %30 ve %40 oranlarında kullanıldı. Ayrıca, mermer tozu çimento ağırlığının %15'ine kadar katkı olarak kullanıldı. Beton karışımların birim ağırlıkları, basınç, çekme ve eğilme dayanımları, elastisite modülü, gerilme-gerinim ilişkisi, yük-eğilme ilişkisi, tokluk değerleri ve geçirimliliği belirlendi. Buna ilaveten, yüksek sıcaklıkların (60ºC, 100ºC ve 200ºC) betonun basınç dayanımı ve birim ağırlık üzerine etkileri araştırılarak, sıcaklığa maruz kalmayan beton numuneler ile karşılaştırmalar yapıldı. Ayrıca, beton numuneleri 300ºC sıcaklığa da maruz bırakılarak, betonun yüzeyindeki değişiklikler incelendi.

Test sonuçlarına göre, mukavemet değerlerinin, elastisite modülünün ve birim ağırlık değerlerin kontrol numunelere göre daha az olduğu tespit edildi. Basınç dayanımı, eğilme dayanımı ve tokluk değerlerindeki en az azalma %20 oranında elektronik plastik kullanılan betonlarda görüldü. Buna karşın, çekme dayanımı, elastisite modülü ve birim ağırlığın artan plastik kullanımıyla azaldığı gözlemlendi. Buna ek olarak, betonun basınç dayanımının artan sıcaklık ile de azaldığı gözlemlenmiş, 300ºC sıcaklığa maruz kalmış numunelerin yüzeylerinde renk değişiklikleri görülmüştür. Ayrıca e-plastik numunelerinin TGA sonuçlarına göre 300ºC sıcaklıkta ağırlık kaybının 200ºC sıcaklığa göre daha fazla olduğu görülmüştür. Bunun yanı sıra, mermer tozu kullanımı ile betonun özelliklerinde ve performansında bazı artışlar görülmüştür.

Anahtar kelimeler: atık e-plastik, mermer tozu, yüksek dayanımlı beton, mekanik özellikler, geçirimlilik, tokluk, dayanıklılık.

DEDICATION

To my kind mother, father and sister and my lovely husband for their infinite support.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABS	Acrylonitrile-Butadiene Styrene
DSC	Differential Scanning Calorimetry
E_c	Elastic Modulus
e-waste	Electronic Waste
e-plastic	Waste Electronic Plastic
f_c	Compressive Strength
GBFS	Granulated Blast Furnace Slag
HDPE	High Density Polyethylene
HIPS	High Impact Polystyrene
HSC	High Strength Concrete
ITZ	Interfacial Transition Zone
LDPE	Low Density Polyethylene
MD	Waste Marble Dust
NSC	Normal Strength Concrete
PC	Polycarbonate
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
SCC	Self- Compacted Concrete
SCLC	Self- Compacting Lightweight Concrete
SEM	Scanning Electron Microscopy
TGA	Thermal Gravimetric Analysis

WPET	Grinded PET Bottles
WPLA	Waste Pet Bottles
w/c	Water/cement ratio
XRD	X-Ray Diffraction

Chapter 1

INTRODUCTION

1.1 Background and Statement of the Problem

Concrete is one of the extensively used material in the construction industry. Approximately three-quarters of concrete volume is occupied by aggregate (Neville, 2002). However, since the resources of naturally available aggregates are continually reducing, there is a tendency to substitute them with other alternatives. Therefore, sustainable concrete production is receiving significant attention in order to protect natural resources and the environment.

In recent decades, the significant growth in plastic consumption and hence the increase in the production of plastic wastes have caused a detrimental impact on the health of the environment due to their low biodegradability potential. In particular, vast amounts of electronic waste (e-waste) are generated every year due to the exponential increase in the market demand for electrical and electronic equipment and their reduced lifespans (Yong et al., 2019). Approximately 9 million tonnes of e-waste were generated in 2005, and it was expected that 2.5 million tonnes of it will be waste electronic plastic (e-plastic) by 2020. The year 2016 statistics for the global e-waste generation indicated approximately 44.7 million tonnes of e-waste while only 20% of the generated waste was recycled; whereas, it is predicted that by 2021, the amount of e-plastic waste will exceed 52.2 million tonnes (Balde et al., 2017).

Therefore, finding effective ways to reuse plastic wastes and improve reuse rate is very important for environmental sustainability. The production of environmentally friendly concrete by using plastic wastes as an aggregate replacement seems to be one of the best reuse approaches applicable due to some advantages of plastics such as low density, and improved chemicals resistivity, energy dissipation, thermal and electrical insulation, long life durability, ease of design and low cost. The detrimental impacts of plastic wastes on the environment could be reduced by reusing them to substitute naturally available aggregates which are about to deplete (Luhar et al., 2019).

Previously, several researches have investigated the influence of using plastic waste as a partial replacement of aggregates or fibers in concrete and mortar. Although there was an extensive research on the use of variety of plastic wastes such as polyethylene terephthalate (PET) (Frigione, 2010; Rahmani et al., 2013; Hannawi et al., 2010; Safi et al., 2013; Albano et al., 2009; Saikia et al., 2014; Islam et al., 2016), polycarbonate (PC) (Hannawi et al., 2010), polypropylene (PP) (Ozbakkaloglu et al.,2017) and polyvinyl chloride (PVC) (Kou et al., 2009), few researchers studied the use of e-plastic as a partial replacement of aggregates in concrete.

In addition to plastic wastes, the utilization of industrial by-products is becoming a more popular research interest among researchers. The marble industry is a growing sector and waste materials produced in this industry are another problem that threatens the environment in North Cyprus and in the world. Almost 70% of marble block is wasted after mining, sawing and polishing processes, where approximately 40% of this waste is sludge and 30% is comprised of cracked material (Hebhoub et al., 2011; Aydın, 2013). Waste marble dust (MD) as limestone origin has the potential to become a sustainable alternative in concrete production since it can be directly used without additional processing (Topçu et al., 2009). Additionally, reuse of MD could protect the environment and provide economic gains.

1.2 The Aim of The Study

The primary focus of this research is to develop an eco-friendly/green concrete that includes waste materials. In the literature, there is a lack of studies on the use of both e-plastic and MD in the production of green concrete. Use of e-plastic waste as an aggregate may affect the mechanical properties of concrete and therefore the utilization of the MD as an additive could modify these properties. Therefore, this study will contribute to the literature by using e-plastic materials as an alternative to fine and coarse aggregates and MD as an additive and/or filler to evaluate whether it is possible to produce acceptable quality of high strength concrete (HSC). Fine and coarse aggregates were replaced with e-plastic at proportions of 0%, 10%, 20%, 30% and 40% by volume of natural aggregates. Also, MD was used as an additive at proportions varying between 0% to 15% by weight of cement in HSC.

The objectives of this study are given below:

1) To determine the effect of e-plastics and MD on fresh and hardened properties of HSC at a constant w/c ratio.
2) To determine the effect of e-plastic replacement to fine and coarse aggregates at different proportions and MD addition on strength properties of HSC.
3) To determine the effect of e-plastic replacement to fine and coarse aggregates at different proportions and MD addition on durability properties of HSC.

4) Highlighting the impact of the high temperatures (60ºC, 100ºC, and 200ºC) on the unit weight and compressive strength of HSC.
5) To investigate the effect of the high temperatures (60ºC, 100ºC, 200ºC and 300ºC) on the surface condition of concrete.
6) To produce more ductile and environmentally friendly concrete.

1.3 Dissertation Outline

Chapter 1 mainly covers the statement of the problem, objectives and significance of this study.

Chapter 2 covers a critical review about the effects of usage of waste materials on mechanical and durability behavior of concrete and mortar. Chapter 3 includes the theoretical background.

Chapter 4 covers the properties of materials used in this study and experimental procedures.

Chapter 5 focuses on presenting and analyzing the experimental findings. It includes the effects of e-plastic and MD on mechanical properties, permeability and also the influence of high temperatures on the mechanical properties and surface condition of concrete. Chapter 6 concludes the overall perspective and findings of this study.

Chapter 2

CRITICAL REVIEW ON THE UTILIZATION OF WASTE MATERIALS IN CONCRETE/MORTAR

The reuse of waste materials or use of recycled materials in concrete as an aggregate and as an additive can contribute to the properties of concrete and leads to low cost and more ecological concrete.

There are many plastic waste products all around the world. Polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC), polyurethane foam, polycarbonate (PC), polystyrene (PS) are the most used recycled plastics. Plastics have very low or no bio-degradability and they persist for a long time in natural environment. Waste and recycled plastic materials can be reused to protect environment. The best way of disposing these plastic wastes is using them in construction industry. Plastic wastes can be shredded, melted or grinded into small particles to replace aggregate partially or totally in cement mortar or in concrete.

MD as an industrial by-product also threatens the environment since the marble industry is a growing sector. Therefore, MD has the potential to become a sustainable alternative in concrete production as it can directly be used without additional processing. It can either be used to replace cement or fine aggregate or as an additive/filler in mortar or concrete production.

2.1 Influence of Plastic Aggregates on the Properties of Concrete and Mortar

2.1.1 Workability

The workability of concrete containing plastic aggregate is affected by the substitution level, w/c and the shape of the aggregate. Most researches regarding recycled plastics showed that when substitution level of plastic aggregates increases, slump has a tendency to decrease as irregular shapes of plastic aggregates leads to low fluidity of concrete.

Ismail et al. (2008), used fabriform shaped plastic wastes which included approximately 80% PE and 20% PS to replace sand by 0%, 10%, 15% and 20%. Plastics had angular and irregular shapes therefore slump decreased sharply with an increase in plastic content. In addition, Batayneh et al. (2007) found that using recycled plastic as fine aggregate, reduced the slump of concrete due to sharper edges of plastic particles and a 25% reduction in the slump of concrete was depicted at 20% replacement ratio. PP as a coarse aggregate substitute at the proportions of 0%, 10%, 20% and 30% by volume decreased the workability of concrete as the inclusion of PP increased due to its non-uniform and angular shape (Ozbakkaloglu et al., 2017). However, according to Wang et al. (2012), the workability of cement mortar was not significantly affected by the use of recycled High Impact Polystyrene (HIPS), as a replacement of sand up to 20% whereas significant decrease was observed at 50% replacement level.

As it is stated above, beside the sharp edges of plastics, non-uniform and angular shapes of plastics also negatively affect workability. However, smooth and spherical shapes of plastics improve the workability of concrete or mortar. Choi et al. (2005) replaced fine aggregates with waste PET bottles (WPLA). WPLA had smooth and spherical shape and it was developed by solidifying the surface of WPLA with granulated blast furnace slag (GBFS). From the slump test results, when WPLA replacement ratio was increased from 25% to 75% and w/c was increased from 0.45 to 0.53, slump increased. The highest increase was observed at 75% replacement level and at 0.53 w/c ratio. This was attributed to the smooth and spherical shape of WPLA and its near zero water absorption.

In addition to the effects of the shape of plastics on the workability of concrete and mortar, the size of plastics is another factor that affects the workability. Albano et al. (2009) used the recycled PET at the proportions of 10% and 20% by volume in concrete with w/c of 0.50 and 0.60. Fine aggregate was replaced with PET aggregates with the particle sizes of 2.6 mm (small size), 11.4 mm (big size) and 50/50 (50% small size + 50% big size) mix of both sizes. For a single particle size, slump of concrete at 10% replacement level was greater than that of concrete with 20% replacement level. Plasticity of fresh concrete decreased when replacement increased. Although PET particles with mixed particle size had no good granulometric distribution, less voids in the fresh concrete provided better results and influenced the plasticity and compaction. As a result, PET particles with mixed sizes provided more continuous dispersion in concrete and higher slump values.

In the study carried out by Saikia et al. (2014), PET aggregates with fine and coarse sizes and a heat-treated pellet-shaped product having spherical/cylindrical shape were used to investigate the size and shape effect when natural aggregates were replaced with PET at the proportions of 5%, 10% and 15% by volume. The w/c ratio of concrete containing PET aggregate varied with shape and size of PET aggregate to achieve the required slump range. As a result, it was concluded that PET aggregate with smooth surface textures and spherical shapes lowered the w/c of concrete for the same slump. However, flaky shaped fine and coarse aggregates increased the water demand due to their sharper edges, angular and non-uniform shapes.

In addition, when melted waste PET bottles having rounded shape was used as coarse aggregate to replace brick chips at the proportions of 0%, 20%, 30%, 40%, and 50% by volume in concrete, less inter-particle frictional resistance and less surface area with fever voids were provided due to smooth and glassy texture and round shape of PET aggregates, respectively. Therefore, workability increased with the increase in plastic addition. Moreover, almost zero water absorption of PET aggregates improved the workability (Islam et al., 2016). On the other hand, Muthadhi et al. (2017), found that utilization of e-plastic as coarse particles in concrete did not significantly affect the workability and the observation was linked to the less inner-friction between cement paste and plastic because of the smooth and slippery surface of plastic. Additionally, the use of PET as a replacement of sand by weight at the proportions of 0%, 10%, 20%, 30% and 50% in self-compacting mortars, enhanced the fluidity of the mixture in direct proportion to the plastic content since plastic possesses smoother surface than the sand (Safi et al., 2013).

2.1.2 Unit Weight

In general, plastic particles are characterized by a lower specific gravity ranging between 0.9 and 1.4 in comparison to natural aggregate. Therefore, concrete incorporated with plastics shows lower density as compared to conventional concrete (Gu et al., 2016).

Yang et al. (2015) used recycled modified PP particles to replace sand by volume at the proportions of 0%, 10%, 15%, 20% and 30% in self-compacting lightweight concrete (SCLC). Reduction in dry density was observed with an increase in plastic replacement levels and reduction reached to 15% at 30% plastic content. In addition, in the study of Ozbakkaloglu et al. (2017), with an increase in inclusion of PP as coarse aggregate, hardened density of concrete decreased, and the reduction reached to 13.1% and 10.1% in NSC and HSC at 30% replacement level, respectively. According to the study on the use of PC and PET plastics to replace sand by volume at the proportions of 0%, 3%, 10%, 20% and 50% in mortar with the w/c of 0.50, it was found that 19% and 24% reduction occurred in dry density of mortars at 50% substitution level of sand with PET and PC, respectively (Hannawi et al., 2010). Islam et al. (2016), also pointed out a gradual decrease in dry density with plastic inclusion.

Therefore, it could be concluded that the decrease in density was attributed to the low specific gravity plastic particles (Yang et al., 2015; Ozbakkaloglu et al., 2017; Ismail et al., 2008; Rahmani et al., 2013; Islam et al., 2016).

2.1.3 Compressive Strength

W/c ratio, replacement level, types and shapes of plastic wastes are the parameters affecting the compressive strength. Concrete’s compressive strength with uniformly shaped plastic aggregate was higher than the concrete with non-uniformly shaped plastic aggregate. Additionally, low elastic modulus of plastic aggregate reduced the compressive strength of concrete. At the same w/c, compressive strength was reported to be inversely proportional to the replacement level (Gu et al., 2016).

According to the studies on the utilization of plastic wastes in concrete or mortar, compressive strength was found to be lower than the reference concrete/mortar at all replacement levels of plastic wastes and it decreased with higher replacement percentages of fine aggregate and with high w/c (Choi et al., 2005; Ismail et al., 2008; Batayneh et., 2007; Kou et al., 2009; Safi et al., 2013; Wang et al., 2012; Hannawi et al., 2010). Almost 33% declining in compressive strength was observed at 75% replacement level in concrete with the w/c of 0.45 (Choi et al., 2005) however, in the study by Safi et al. (2013), a 33% reduction was observed at 50% replacement level. Furthermore, when replacement level of fine aggregate with PVC granules ranged from 5% to 45%, the reduction in compressive strength ranged from 9.1% to 47.3%, respectively (Kou et al., 2009). When 50% of sand was replaced with HIPS, the reduction in compressive strength reached to 49% (Wang et al., 2012). However, in the study of Hannawi et al (2010), the decrease in compressive strength reached to 69% and 63.9% when 50% PET and PC were used to replace sand in mortar, respectively. Contrarily, even at 20% replacement level, sharp reduction in compressive strength up to 72% was observed according to the Batayneh et al. (2007). On the other hand, although Frigione (2010) found slight decrease in compressive strength when grinded PET bottles (WPET) were used as fine aggregate by weight of 5%, higher reductions were observed at high w/c due to fact that the accumulation of higher bleeding water around the plastic particles resulted in weak bond formation.

Therefore, the primary reason of compressive strength reduction was directed towards the poor bond between plastic aggregate and cement matrix (Hannawi et al., 2010; Ismail et al., 2008; Frigione, 2010; Wang et al., 2012) due to smooth surface of plastics (Wang et al., 2012) and lower strength of plastics than conventional aggregates (Batayneh et al., 2007; Safi et al., 2013). However, failure under compression became more ductile with an increase in plastic content (Hannawi et al., 2010). Likewise, annular cylindrical form of plastics provided physical adhesion between cement paste and plastic as they were not pulled out from the fracture surface of mortars (Safi et al., 2013).

Moreover, when PET granules were used in two groups of mortar in which one of mixtures was prepared only by PET granules and the other included a portion of sand, higher compressive strength was observed for the mixture of PET granules and fine aggregates. In addition, 50% of cement mass was replaced with blast furnace slag and mortars' compressive strength was directly proportional to the slag content (Akçaözoğlu et al., 2010).

In addition to the studies in which fine aggregate was replaced with plastic wastes, when PET, shredded e-plastic, HIPS and PP were used as coarse aggregates, concrete's compressive strength decreased upon increasing plastic content (Islam et al., 2016; Akram et al., 2015; Senthil Kumar et al., 2015; Ozbakkaloglu et al., 2017). The reduction reached to 34% at 15% of e-plastic inclusion. However, utilizing 10% of fly ash as an additive improved the compressive strength regardless of plastic content (Akram et al., 2015). In the study of Senthil Kumar et al. (2015), the reductions in compressive strength reached to 47.72%, 47.41% and 64.14% at 50% replacement level at w/c of 0.45, 0.49 and 0.53, respectively. According to

Ozbakkaloglu et al. (2017), the reductions in HSC occurred at a higher rate than that of normal strength concrete (NSC). The lowest reduction of 1.8% was observed in NSC at 10% substitution level compared to the control concrete.

As the above stated reasons of the reduction in compressive strength when fine aggregates were replaced with plastic wastes, especially bleeding in concrete with higher w/c and almost zero water absorption capacity of plastics caused accumulation of water at ITZ and affected the compressive strength negatively. In addition, smooth surface of plastics resulted in relatively weak bond between cement paste and plastics (Islam et al., 2016). However, concrete with PP aggregates performed ductile behavior under compression with a more progressive failure. Cracks on NSC containing PP aggregates were visible whereas they were more pronounced on HSC specimens with PP particles (Ozbakkaloglu et al., 2017).

In addition to the above mentioned studies, according to Saikia et al. (2014), concrete’s compressive strength containing PET particles decreased independent from the shape and size of PET aggregate due to the nature of PET substitutes since it is chemically inert. The size and shape of PETs were controlling the w/c as it functions in the concrete’s workability. In general, concrete’s compressive strength was more than 75% of the control concrete when pellet shaped plastic and 5% of plastic fine were used. Rough surface of plastic fine provided better binding with cement paste and its particle size distribution matched with normal aggregate than pellet shaped plastic which were almost similar in size.

Furthermore, Albano et al. (2009) found that compressive strength of concrete decreased with the PET addition. However, higher compressive strength values were obtained in the blends with 10% replacement ratios. The compressive strength at 20% replacement level with 11.4 mm big PET particle size resulted in very low values due to formation of honeycombs and type of failure. For example, there were pores in the external surface of some cylinders with honeycomb shape due to low workability. In addition to this, higher reductions were observed at higher w/c.

In addition, in the study of Marzouk et al. (2007), granular PET particles finer than 5 mm, 2 mm and 1 mm were utilized in cementitious concrete composites to replace sand at proportions of 2, 5, 10, 15, 20, 30, 50, 70 and 100% by volume. A slight decrease of 15.7% in compressive strength occurred compared to the control mortar until 50% replacement level. For the same replacement level, mortars with PET particles finer than 1 mm and 2 mm performed similar behavior whereas high mechanical properties which were close to the reference mortar were observed in mortar with PET particles finer than 5 mm.

Contrarily, an increase in compressive strength was observed up to certain replacement levels. Rahmani et al. (2013), found that the compressive strength values of concrete with two different w/c of 0.42 and 0.54 increased by 8.86% and 11.97% at 5% replacement of the fine aggregates with grinded PET particles, respectively. However, a reduction in compressive strength was observed with a further increase up to 15% replacement level. Furthermore, up to 15% replacement of sand with PP, enhancement of compressive strength was found in the study of Yang et al. (2015). This was attributed to the filling of some voids in concrete with plastic particles effectively at lower plastic contents. Above 20% replacement level, compressive strength decreased due to excess water around the plastic particles that may weaken the ITZ. However, this reduction was not significant. In addition, according to Muthadhi et al. (2017), an increase in concrete's compressive strength was observed up to 10% substitution of coarse aggregate with e-plastic by volume. However, it decreased at 20% replacement level.

Furthermore, when e-plastic of acrylonitrile-butadiene styrene (ABS) was utilized as fine particles in mortar at the proportions of 2.5%, 5%, 7.5%, 10% and 12.5% with a w/c of 0.5, higher compressive strength values were observed at the replacement levels of 7.5% and 10% compared to the reference mortar. However, the highest reduction in compressive strength occurred at 12.5% replacement level. Since w/c was kept constant, the reason of variations in compressive strength results was attributed to the variation in granulometry (Makri et al.,2019).

2.1.4 Splitting Tensile Strength

At constant w/c, splitting tensile strength of e-plastic concrete is gradually less than that of conventional concrete with a higher plastic content. As in compressive strength, substantial decreases in splitting tensile strength occur with irregular shape plastic aggregates than that of concrete with plastic aggregates having uniform shapes. Additionally, lower elastic modulus of plastic particles than that of natural aggregates reduces the concrete's splitting tensile strength (Gu et al., 2016).

Splitting tensile strength of cement- based materials with plastic wastes which were used to replace fine aggregate reduced upon higher plastic content (Batayneh et al., 2007; Rahmani et al., 2013; Wang et al., 2012; Kou et al., 2009; Frigione, 2010) yet had a lower effect than the compressive strength (Batayneh et al., 2007; Wang et al., 2012). 15% content of PET caused the splitting tensile strength to reduce by 15.9% and 18.06% for the w/c of 0.42 and 0.54, respectively (Rahmani et al., 2013).

However, according to the study of Wang et al. (2012), the reduction (%1.5) was not significant at 10% replacement of sand with HIPS whereas 20% reduction was obtained at 50% substitution. Frigione (2010), concluded that replacing sand by 5% of PET particles by weight resulted in the slight reduction and reductions became higher in correspondance with higher w/c. The poor bonding between plastics and cement paste caused a reduction in the strength of the concrete due to plastics' smooth surface (Rahmani et al., 2013; Kou et al., 2009). In addition, Kou et al. (2009) found that when the ultimate strength was reached, expulsion of PVC particles from cement paste was encountered without particles breakage.

Contrarily, SCLC's splitting tensile strength containing PP particles improved up to 15% sand substitution since bridging action occurred in fracture surface due to short-column plastic particles. However, gradual decrease was observed with further increase in replacement level due to weakened ITZ (Yang et al., 2015).

Furthermore, utilizing coarse plastics in concrete reduced its splitting tensile strength considerably as a function of the plastic content (Akram et al., 2015; Senthil Kumar et al., 2015; Ozbakkaloglu et al., 2017). Likewise the compressive strength, the reason behind this reduction could be linked to the poor bonding between the cement-plastic interface (Akram et. al., 2015; Ozbakkaloglu et al., 2017), due to smooth surface texture of plastics, and hydrophobic nature of plastics (Ozbakkaloglu et al., 2017). Reductions in splitting tensile strength reached to 13.7% and 20.3% at 30% replacement of coarse aggregates with PP for NSC and HSC mixes, respectively (Ozbakkaloglu et al., 2017). In addition, the reduction in splitting tensile strength ranged from 40.48 to 47.99% at 50% replacement of coarse aggregates with HIPS when w/c ranged between 0.45 and 0.53, respectively (Senthil Kumar et al., 2015). However, the failure of concrete with e-plastic occurred smoothly than that of control concrete which broken suddenly (Akram et al., 2015). Additionally, HIPS had ability to show large elastic deformation before fracture and able to resist post-failure loads. As a result, concrete with HIPS showed ductile behavior without separation into two halves (Senthil Kumar et al. 2015). On the other hand, slight increase in splitting tensile strength was observed up to 10% replacement of coarse aggregate with e-plastic whereas it decreased at 20% replacement level due to weak bond between plastic and cement paste (Muthadhi et al., 2017).

According to the study carried out by Albano et al. (2009), splitting tensile strength values of concrete with a w/c of 0.50 decreased regardless of the size of PET however, the reduction was more significant at 20% replacement level due to the great porosity of concrete. Nevertheless, higher reductions were observed in concrete with a w/c of 0.60 compared to that of concrete with a w/c of 0.50 but mixed particle size provided the smallest decrease. Saikia et al. (2014) showed that maximum reductions occurred in concrete with flaky shaped coarse plastic due to high w/c whereas minimum reductions were occurred in concrete with pellet shaped plastics having smooth and spherical shapes due to its lowest w/c. Since the characteristics of ITZ is one of the most important factors affecting splitting tensile strength, smooth surface and free water at the surface of plastic particles affected splitting tensile strength negatively.

2.1.5 Modulus of Elasticity

Concrete's elastic modulus with plastic aggregate is affected by several parameters such as type of plastic, w/c, substitution level of plastics, porosity of the aggregates, and ITZ. Due to lower bulk density of plastic aggregates than that of the typical natural aggregate, elastic modulus decreases with an increase in plastic content. Also, at same w/c, elastic modulus is less than that of conventional concrete and the concrete with non-uniform shaped plastics resulted in lower elastic modulus (Gu et al., 2016).

Use of plastic wastes as fine aggregate in concrete or mortar production resulted in the reduction in modulus of elasticity. In addition, approximate linear relation between reduction in elastic modulus and increase in plastic content was observed. Reasons of the decrease in elastic modulus could be attributed to the lower elastic modulus of plastic aggregates than natural aggregates, and the poor bond between cement matrix and plastic aggregates (Hannawi et al., 2010; Rahmani et al., 2013). Likewise in the study of Kou et al. (2009), use of PVC as fine aggregate reduced the concrete's elastic modulus with an increase in replacement level due to lower elastic modulus of PVC particles and the reduction was 60.2% at 45% replacement level.

On the other hand, in addition to the influence of plastic wastes as fine aggregate on the elastic modulus of concrete or mortar, use of plastic wastes as coarse aggregate in concrete reduced the elastic modulus due to lower elastic modulus of plastics than natural aggregates and the reduction became higher when replacement level (Senthil Kumar et al., 2015; Ozbakkaloglu et al., 2017) and w/c (Senthil Kumar et al., 2015) increased. According to Senthil Kumar et al (2015), the weak bond between plastics and cement matrix was the factor affecting the modulus of elasticity. Up to 32.3% and 41.6% reductions were observed in NSC and HSC mixes at 30% replacement levels, respectively whereas minimum reduction of 5.7% was observed in NSC at 10% replacement level (Ozbakkaloglu et al. 2017).

Likewise the negative effect of plastic wastes on modulus of elasticity mentioned above, according to Albano et al. (2009) and Saikia et al. (2014), higher elastic modulus was observed in concrete at 10% replacement of PET for a fixed particle size due to the effect of aggregate on elasticity. Resistance of PET to the applied stress is lower than the sand, therefore, it will deform less with the application of equivalent stress. Consequently, it results in regular decrease in modulus of elasticity. As it was also stated by Jones et al. (1971), elastic modulus is affected by the type of aggregate because the type of deformation produced in concrete partially depends on the elastic deformation of aggregate. However, particle size of PET aggregates had lesser effect on elastic modulus as the fractions of concrete components have a direct effect on elastic modulus of concrete. As a result, it was observed that particle size had no adverse effect on elastic modulus for the same amount of PET (Albano et al., 2009). In addition, according to Saikia et al. (2014), inclusion of flaky shaped plastic coarse and plastic fine aggregate increased the water demand and w/c. Therefore, concretes with plastic coarse and plastic fine were more porous than others and had lower modulus of elasticity.

On the other hand, Makri et al. (2019) found that elastic modulus of mortar tended to show a decrease when ABS was used instead of fine aggregate. However, elastic modulus of mortars at 7.5% and 10% replacement level was higher than that of the control mortar.

2.1.6 Flexural Strength

At same w/c, flexural strength of concrete reduces with increasing substitution level of plastic aggregate (Gu et al., 2016).

Concrete/mortar’s flexural strength incorporating plastic wastes as fine aggregate reduced with high replacement level (Ismail et al., 2008; Safi et al., 2013; Batayneh et al., 2007) and this reduction was linked to weak resistance of plastic (Safi et al., 2013) and the nonhydrophilic nature of plastics as well as weak adhesive strength between plastic particles and cement paste (Ismail et al., 2008). According to Batayneh et al. (2007), slighter change in flexural strength as compared to the compressive strength was observed. Juki et al. (2013), realized that when 25% PET was utilized to substitute fine aggregate, flexural strength decreased by 5% but when substitution level increased to 50% and 75%, it decreased by 24% and 48%, respectively. However, 32.8% decrease was depicted at 50% plastic content in the study of Marzouk et al. (2007). On the other hand, according to Hannawi et al. (2010), flexural strength of mortars up to 10% PET particles and not more than 20% PC aggregates did not change significantly. As it was observed by Marzouk et al. (2007), the reductions at 50% replacement level were 17.9% and 32.8% in mortars with PET and PC aggregates, respectively. Moreover, delay in fracture phases was observed due to tenacity characteristics of plastic particles.

According to the studies in which coarse aggregates were replaced with plastic wastes, when replacement level increased from 10% to 30%, the reductions in flexural strength were found to be ranged from 5.1% to 29.6% for NSC mixes and 5.4% to 30.4% for HSC mixes (Ozbakkaloglu et al., 2017). At higher replacement levels such as at 50% substitution of coarse aggregates with HIPS, reduction in flexural strength was 36.99%, 37.38% and 41.58% for w/c of 0.45, 0.49 and 0.53, respectively. However, although a reduction in flexural capacity of concrete was observed upon increment of HIPS content, concrete with HIPS did not split into two halves and HIPS acted as fiber and delayed the crack propagation after reaching the ultimate load (Senthil Kumar et al. 2015).

Likewise, Saikia et al. (2014) concluded that flexural capacity reduced with respect to PET additions. However, concrete beams with plastic coarse and plastic fine aggregates did not split into two after failure and brittle failure of specimen was prevented since elongated and flaky particles bridged the crack and improved the concrete’s post-crack capacity.

Akçaözoğlu et al. (2010) showed that 28-days flexural capacity of mortars was not affected by the inclusion of PET particles. When the findings were analyzed against the control mixture, the ratios of flexural strength of mortars with PET aggregates, and PET and sand together were roughly 46%. Flexural strength values of mortars in which cement was replaced with slag were equal to the mortars without slag.

Contrarily, an increase in the flexural strength was also observed in some studies. Up to 15% replacement of sand with PP particles, flexural strength increased. However, further increase in plastic content decreased the flexural strength gradually. Reduction up to 30% plastic replacement level was found to be insignificant whereas the reason of reductions was attributed to the incompatible properties between plastics and cement paste. However, improvement in the ductility of concrete was observed at higher plastic contents (Yang et al., 2015). Additionally, Rahmani et al. (2013), found that using PET particles at 5% of sand increased the flexural strength whereas it started to decrease at further increase in PET particles. In addition, beam did not fail completely since PET particles bridged the two cracked surfaces of beam due to their spherical volume and flexibility.

2.1.7 Stress- Strain Relationship

According to peak value and shape of stress-strain curves obtained from the compression tests, although conventional concrete performed brittle behavior, increase in toughness and ductility were observed in concrete with WPET (Frigione, 2010).

Additionally, Wang et al. (2012) found that failure of mortar specimens with HIPS aggregate was more gradual and ductile according to stress-strain diagrams under compression. In addition, maximum strain was directly proportional to the plastic content.

On the other hand, flexural load-deflection curves showed the improvement in ductility with the inclusion of plastics which had ability to prolong crack propagation (Hannawi et al., 2010).

2.1.8 Microstructure Analysis

According to the analysis by scanning electron microscopy (SEM), a weak bond between the plastic aggregate and matrix was observed in the study of Hannawi et al. (2010).

In another study carried out by Marzouk et al. (2007), high level of compactness was observed when substitution volume was 50% and less. However, the structure became more cavernous above 50% substitution level and resulted in the decrease in the bulk density and mechanical properties.

According to the SEM analysis of the study carried out by Safi et al. (2013), ITZ of 28-day mortar at 50% replacement level was dense enough without cracks. Besides, adhesion between plastic and cement paste was observed due to annular cylindrical form of plastic.

According to Choi et al. (2005), GBFS on the surface of WPLA was able to react with calcium hydroxide made by C_2S and C_3S to form calcium silicate hydrate (C–S–H). GBFS consumed the calcium hydroxide so that ITZ was strengthened and narrowed.

2.1.9 Water Absorption and Porosity

Replacing sand by PET particles caused the water absorption percentages to reduce at 10% replacement level in comparison with 20% replacement level due to lower porosity at both w/c (0.50 and 0.60). However, blends with bigger PET particles increased the water absorption percentage (Albano et al., 2009). Additionally, Safi et al. (2013) found that water absorption decreased when plastic waste increased in mortar due to filling effect of voids. However, it started to increase at and above 30% replacement level. According to Hannawi et al. (2010), although no significant effect was observed on water absorption and apparent porosity at 3% replacement level, higher plastic content increased the water absorption and apparent porosity.

Makri et al. (2019) found that the porosity and water absorption values of mortar showed an increase when replacement levels of fine aggregates with ABS were 2.5%, 5.0% and 12.5% whereas they were less than that of control mortar at 7.5% and 10% plastic content. It was concluded that the obtained results were in consistent with the obtained compressive strength results.

In addition, positive effect of the use of fly ash together with e-plastic was stated in the study of Akram et al. (2015). Water absorption and porosity of concrete without fly ash was higher than concrete with 10% fly ash addition at all e-plastic replacement levels. Additionally, water absorption and porosity exhibited higher by means of higher levels of coarse aggregates replacements with e-plastics due to inter-particle voids in concrete.

Furthermore, Akçaözoğlu et al. (2010), found that using GBFS in mortars caused a reduction in the resistance to water absorption as compared to the case of only cement. Additionally, porosity of mortars with PET and sand were higher than that of mortars with PET only while its water absorption was lower than that of the PET only.

2.2 Influence of High Temperatures on Concrete Properties with and without Plastics

2.2.1 Unit Weight

Unit weight of concrete reduced when concrete specimens were exposed to high temperature (Bingöl et al. 2008; Arioz, 2007). According to unit weight results of normal strength concrete (C20 and C35) that was kept at the temperatures of 50, 100, 150, 200, 250, 300, 350, 400, 500, 600 and 700ºC for 3 hours and then cooled to room temperature either in water or in laboratory conditions, there was reduction in unit weight results with an increase in temperature. Up to 400ºC and at 400ºC, the reductions in unit weight for both concrete types were 4% and 6%, respectively. However, maximum reductions were observed at 600ºC and 700ºC. The reason could be attributed to the water released from the cement paste and the growth of air voids in concrete (Bingöl et al., 2008). In the study of Arioz, (2007), the reduction in weight of concrete specimens ranged from 5% to 45%, when concrete specimens exposed to temperatures between 200 to 1200ºC for 2 hours, respectively. Reduction in weight occurred gradually between 200 and 800ºC whereas sharp reduction was observed beyond 800ºC. The reason of weight loss could be attributed to the change in mechanical behavior of concrete. At higher w/c ratios, higher losses were observed. Additionally, lower losses occurred in concretes produced with river gravel aggregate.

2.2.2 Compressive Strength

Study on the effect of various temperatures on concrete without plastics highlighted that the concrete's compressive strength had an inverse relation with increasing temperature. According to relative compressive strength values, slight reduction up to 600ºC and sharp reduction beyond 600ºC were observed in crushed limestone aggregate concrete whereas the reduction occurred gradually but significantly in river gravel aggregate concrete due to their siliceous composition. In addition, decomposition of crushed limestone aggregate occurred at the temperature nearly 600ºC. At 600ºC, the relative strengths of limestone concrete and river gravel concrete were 90% and 50%, respectively (Arioz, 2007).

Besides the effects of exposed temperatures, cooling method also affected the compressive strength of concrete. According to Bingöl et al. (2008), concrete's compressive strength was influenced by the method of cooling where samples cooled using air flow resulted in higher capacity than that of the water-cooled approach. For example, the highest decrease of 62% and 55% was observed in air cooled C20 and C30 specimens respectively, whereas 68% reduction was observed in both water-cooled C20 and C30 specimens at 700ºC.

When concrete with and without plastic wastes were exposed to high temperatures, increase with respect to the plastic content resulted in more pronounced reduction in compressive strength when temperature increased (Ozbakkaloglu et al., 2017; Senthil Kumar et al., 2018; Correira et al., 2014). Ozbakkaoglu et al. (2017), concluded that when 28-day concrete specimens with and without PP were exposed to 75ºC, 100ºC and 200ºC for 4, 24 and 96 hours, respectively, the compressive strength decreased slightly regardless of its strength class at the temperatures of 75°C and 100ºC but reductions were significant at 200ºC compared to the concrete mixes under the ambient temperature. This was attributed to that significant water vaporization occurs inside the concrete above 100ºC however, pore pressure and crack propagation were developed in concrete since the water vapor's discharge was limited due to compact concrete matrix. In the study carried out by Senthil Kumar et al. (2018), concrete specimens were exposed to high temperatures for 1 hour and sprinkling water was applied on concrete surfaces for cooling. The decrease in concrete's compressive strength in which coarse aggregates were replaced with HIPS at the proportions varying from 10 to 50% were ranged between 7.97 and 13.60%, 11.95 and 39.27%, 22.53 and 50.91% at the temperatures of 100, 200 and 300ºC, respectively.

In addition, according to the Correira et al. (2014), the reduction of concrete's compressive strength upon exposure to temperature of 600 and 800ºC for 1 hour was also attributed to the physical- chemical reactions occurred by various concrete constituents and development of thermal gradients during the heating stage. Additionally, the thermal decomposition of PET aggregates increased the degradation and porosity of concrete.

2.2.3 Surface Condition

When concrete specimens were exposed to high temperatures, damages might be nearly examined by investigating the concrete surfaces.

Bingöl et al. (2008), observed color changes on the surface of concrete when the temperature changed from 50 to 700ºC and cracks were in macro level when temperature reached to 700ºC. Likewise in the study of Arioz. (2007), up to 400ºC, no noticeable effect was observed on concrete surfaces. However, cracks were observed on concrete surface at 600ºC. With an increase of temperature to 800ºC, cracks became more distinct and increased at 1000ºC. As a result, when temperature reached to 1200ºC, excessive cracks generated the spalling of samples and specimens decomposed completely and lost their binding properties.

According to the study of Albano et al. (2009) in which PET aggregates were used, similar morphological changes were observed on the surfaces of slabs in both 10% and 20% replacement levels. At 200ºC, no significant variations on the surface morphology were observed compared to the unexposed concrete specimens. That means concrete or PET are not affected by chemical reactions at that temperature. However, the changes on surface morphology with color variations and surface deterioration became evidential at and above 400ºC due to chemical reactions between constituents of concrete and also demolishing and surface disassociation of PET particles. This influence was more obvious at 600ºC. Therefore, it can be said that thermo-degradative behavior of PET is one of the factors that affects the morphology. In addition, in the study of Ozbakkaloglu et al. (2017), the surface morphology did not vary significantly at 75 and 100ºC compared to the untreated concrete samples since the temperatures of 75 and 100ºC were lower than the fusion point of PP. However, a significant change on surface morphology was observed in concrete with PP aggregates compared to the control concrete at 200ºC (Ozbakkaloglu et al. 2017).

Moreover, in the study of Senthil Kumar et al. (2018), color changes and crack formations occurred in concrete surfaces at higher temperatures. At 100ºC, there were no visible cracks and color change whereas color changes were observed without any visible cracks at 200ºC. At 300ºC, visible hairline cracks were occurred on concrete surface and plastics close to the concrete surface burned. However, HIPS inside the concrete did not changed. Moreover, according to Correira et al. (2014), rise in temperature caused an increase of width and length of cracks on concrete surfaces. Spalling also occurred at the corners of some of the specimens. In addition, black or brown stains were observed on the surface of specimens those included plastics whereas reference concrete became brighter due to water loss. Additionally, extensive voids were observed in concrete due to decomposition of plastic particles and especially void became higher at 800°C due to complete decomposition of plastics.

2.3 Influence of Marble Dust on the Properties of Concrete

2.3.1 Workability

Utilization of MD in concrete either to substitute cement or fine aggregate decreased the workability of concrete.

Khodabakhshian et al. (2018) used MD to replace cement at the proportions ranging from 5 to 20% and found that increase in replacement level resulted in the increase in superplasticizer demand to achieve required workability.

Furthermore, when MD was used at the proportions ranging from 10 to 60% to substitute fine particles in concrete by weight, workability of concrete decreased when replacement level increased. The loss in workability was due to the angular shape of MD and increased surface area. Use of MD also increased the cohesiveness of mix that led to decrease in workability (Vardhan et al., 2009).

2.3.2 Compressive, Splitting Tensile and Flexural Strengths

Topçu et al. (2019) used waste MD in self compacted concrete (SCC) as filler material to replace binder of SCC at the various contents from 50 kg/m^3 to 300 kg/m^3. Higher content of MD caused a reduction of compressive strength. Up to 100 kg/m^3, differences in compressive strength was not vary too much. However, highest reductions were observed at the MD contents of 250 kg/m^3 and 300 kg/m^3 due to poor workability. As a result, hardened concrete properties were improved up to 200 kg/m^3 MD content due to achieved acceptable fresh properties. However, according to study carried out by Sadek et al. (2016), MD was used as mineral additive to cement content in SCC. Compressive strength increased by 1.7%, 3.9% and 9.5% by using 30%, 40% and 50% MD, respectively due to filler effect of MD.

Besides the studies of the use of MD as filler and mineral additive in SCC, in the study of Ergün (2011), MD was utilized as a partial replacement of cement at the proportions of 5%, 7.5% and 10%. At 5% replacement level, concrete's compressive strength increased due to the filler effect of MD. However, the lowest strength value was observed at 10% MD content and this was attributed to the decrease in pozzolanic reactions. Additionally, Uysal et al. (2011) used MD to replace cement at the contents of 10%, 20% and 30% by mass in SCC where water/binder ratio was kept constant as 0.33. Specimens with MD performed well in terms of compressive strength due to denser matrix and dispersion of cement grains (Bonavetti et al., 2003). In addition, 5% replacement of cement with MD increased the concrete's compressive strength whereas it was inversely proportional to the replacement level with the highest reduction at 20% replacement level (Khodabakhshian et al., 2018).

In addition to the above mentioned studies, MD was also used as an alternative of sand in concrete or mortar. Demirel (2010), used MD finer than 0.250 mm to substitute fine aggregates in concrete at 0%, 25%, 50% and 100% by weight. Compressive strength increased at higher MD content. When fine aggregate was replaced fully, improvement in compressive strength was 10% compared to that of control concrete. Binici et al. (2007) also used MD finer than 1 mm instead of sand at the proportions of 5%, 10% and 15% by weight. Concrete's compressive strength increased due to increase in MD content. At 15% replacement level, 24% increase in 28 days compressive strength was found. However, according to Vardhan et al. (2009), the increase in compressive strength reached to 22.4% up to 40% replacement of fine aggregates with MD due to its filler effect. It also improved the pore structure and microstructure of the matrix. However, compressive strength decreased and became stable at the replacement levels of 50% and 60%. This could be attributed to the loss of workability that affected the packing of constituent materials.

On the other hand, Baboo et al. (2011) used MD to replace cement and marble granules to replace fine aggregates by weight in mortar at the proportions of 0%, 5%, 10%, 15% and 20%. According to compressive strength values, there was an increase up to 10% substitution of fine aggregates with MD however, beyond 10%

replacement level, slight reduction was observed. However, when replacement of cement with MD ranged from 5 to 20%, compressive strength decreased remarkably.

Moreover, Khodabakhshian et al. (2018), found enhanced concrete's splitting tensile behavior at 5% and 10% replacement of cement with MD. However, splitting tensile strength worsened with a further increase in replacement level (at 20%) compared to that of the control concrete.

In addition to the effects of MD on compressive and splitting tensile strength, the increase in MD content resulted in the reduction of the flexural strength of SCC. Lowest flexural strengths were observed in SCC where MD contents were 250 kg/m^3 and 300 kg/m^3 due to poor workability. However, flexural strength improved when binder of SCC was replaced with MD contents up to 200 kg/m^3 (Topçu et al., 2009).

When 5% of cement was replaced with MD, concrete's flexural strength did not change compared to that of the control concrete. With an increase in replacement level, flexural strength decreased yet not substantially (Ergün, 2011).

Contrarily, according to Baboo et al. (2011), flexural strength of mortar increased with a substitution of fine aggregate with marble granules at the proportions ranging from 5 to 20%.

2.3.3 Modulus of Elasticity

With a fully replacement of fine aggregates with MD, the highest dynamic modulus of elasticity was obtained (Demirel, 2010).

Another aspect highlighted by Khodabakhshian et al. (2018) was regarding 0%, 5%, 10% and 20% replacement of cement with MD, the highest concrete's elastic modulus was achieved at 5% replacement level. However, substitution of MD particles at 10% and 20% caused a reduction in the modulus of elasticity of concrete.

2.3.4 Microstructural Analysis

According to microstructure characteristics, differences in CH ($Ca(OH)_2$) morphology were observed in samples with and without MD. Although CH crystals were large and euhedral in the specimen without MD, dispersed CH crystals with smaller sizes were observed in matrix of specimen at 50% replacement level. This was attributed to the filler effect of MD (Demirel, 2010).

According to the microstructural analysis of the study carried out by Vardhan et al. (2009), MD did not show substantial effect on hydration of cement. However, significant densification was observed in mixes with MD that reflects the filler effect of MD. In addition, dispersion of C-S-H was the indication of better binding ability hence dense and non-porous microstructure.

2.3.5 Permeability

From 5 to 15% replacement of fine aggregates with MD, water penetration depth decreased significantly compared to the control concrete. This was explained by the densification of aggregate-cement interfacial zone due to the water absorption of MD (Binici et al. 2007). Additionally, the porosity of concrete was reduced with an increase in substitution level of fine aggregates with MD due to its filler effect on cement hydration (Demirel, 2010; Kristulovic et al., 1994).

2.4 Influence of High Temperature and Marble Dust on Compressive Strength and Microstructure Analysis of Concrete and Mortar

Bayraktar et al. (2019) used MD to replace cement at the proportions of 5%, 10%, 15%, 20% and the mortars were subjected to high temperatures of 150, 300, 700 and 900ºC for 2 hours. 28 days compressive strength results showed reduction with the addition of MD. When air cooled specimens were exposed to 150ºC, there was a slight strengthening in compression however with a further increase in temperature, there was a reduction compared to the reference mortar. However, specimens those were cooled with sprinkling showed reduction with an increase in temperature. Compared with the pure PC cement, mixtures with mineral additive includes less calcium hydroxide and this could be one of the reasons of increase in strength up to 150ºC. According to the microstructure analysis of mortar specimens exposed to the high temperatures, distribution of aggregate, development of crack and void structure could not be determined up to 300ºC whereas development of cracks between aggregate grains and binder was observed beyond 300°C.

Keleştemur et al. (2014) was used MD as fine sand at proportions varying from 20 to 50% by volume with a glass fibre in cement mortar. When mortars were exposed to 400, 600 and 800ºC, slight decrease in compressive strength up to 600ºC and sharp reduction beyond 600ºC were observed. The reason was attributed to the expulsion of crystal water resulted in the diminishing of $Ca(OH)_2$ and alteration of the morphology and formation of micro-cracks that weakened the ITZ. Nevertheless, utilization of MD improved the resistance of mortars to the high temperature by reducing the voids. Additionally, micro-cracks started to occur nearly 400ºC and grew until 800ºC. Formation of micro-cracks could be the reason of reduction in compressive strength by negatively affecting the ITZ and bond between cement paste and aggregate. Moreover, there were big changes on morphology of specimens at 600 and 800ºC due to micro-cracks, increase in voids hence porosity, decomposition of $Ca(OH)_2$ crystals and disrupted C-S-H boundaries.

Chapter 3

THEORETICAL BACKGROUND

3.1 Fresh Properties of Concrete

3.1.1 Workability

Workability is a fresh concrete property which determines the ease of placement and resistance of concrete against segregation. Therefore, concrete should be workable enough to be transported, placed, compacted and finished easily without segregation. Water content of the mix is one of the most important factors that affects the workability. Besides, maximum aggregate size, shape, grading and texture of aggregates, presence of admixtures and fineness of cement are the factors affecting workability when water content and other mix proportions are constant (Neville, 2002).

3.2 Strength of Concrete

Structure of the cement paste has a direct impact on the strength of concrete since hydration products of cement and their volumetric proportions affect the strength (Neville, 2008). Furthermore, w/c, degree of compaction, age, temperature, grading, shape, size, surface texture, strength and stiffness of aggregate, aggregate/cement ratio, and ITZ are the factors influencing the strength (Neville, 2008).

Strength gaining is more rapid in mixes with lower w/c. It is affected by the w/c ratio and cement properties as well as admixtures. In addition, strength depends on age and temperature. The rate of hydration of the cement increases with an increase in temperature and concrete strength increases with hydration process of cement. At any stage of hydration, w/c influences the porosity of hardened cement paste, hence, for a fully compacted concrete, the volume of the voids in the concrete is affected by the w/c and the degree of compaction. The strength of the concrete increases with a decrease in w/c (Neville, 2002). As an example, when two cement blends were prepared by using the same materials, w/c has a substantial influence on the properties of concrete due to porosity (Porrero et al. 2004).

Shape and surface texture of aggregate are other important factors affecting the strength and mechanical bond between aggregate and cement paste. Rough and angular crushed aggregates ensure better bond and less micro-cracking hence they lead cracking at lower stress than smooth gravels. Similarly, aggregates with different shapes and stiffnesses resulted in the variations in mechanical properties of concrete (Sakr et al. 2005).

Furthermore, angular aggregate particles improve the flexural strength of concrete more than the rounded particles however, same flexural strength values can be achieved with rounded shape aggregate as they require less water to achieve the required workability (Neville, 2002; Neville, 2008).

The ITZ between coarse aggregate and cement paste, is the place where micro-cracking is initiated and stress concentrations arise due to the difference in elastic modulus and Poisson's ratio of the two materials. In addition, the porosity at ITZ is higher than elsewhere due to the presence of large crystals of $Ca(OH)_2$. However, with the addition of pozzolana, the strength of the ITZ can be improved with time due to the reaction between $Ca(OH)_2$ and pozzolana (Neville, 2002). For example, in the study of Choi et al. (2005), the surface of the plastic waste was coated with GBFS and as a result, GBFS was able to react with $Ca(OH)_2$ made by C_2S and C_3S to form C-S-H. Therefore, the surface of the plastic waste was strengthened and ITZ was narrowed.

3.2.1 Relation Between Compressive and Tensile Strengths

With the increase of concrete’s compressive strength, the tensile strength also increases. The ratio between splitting tensile and compressive strength is affected by the grading of aggregate, shape and surface texture of coarse aggregate, properties of fine aggregate, moisture condition of concrete, specimen size and testing method of concrete in tension. Age also affects the relationship between compressive and splitting tensile strength.

Direct and splitting tensile strengths are not affected significantly by the aggregate type. However, higher flexural strength values can be achieved with angular crushed aggregate rather than the use of rounded natural gravel because of the improved bond between aggregate and cement paste. Surface texture and shape of aggregate have little effect on concrete’s compressive strength. Hence the ratio of flexural to compressive strength becomes higher when angular crushed aggregate is used (Neville, 2002; Neville, 2008).

3.2.2 The Strength and Behavior of Concrete at High Temperatures and in Fire

Under high temperatures, mechanical properties of concrete; strength, elastic modulus and volume stability decrease significantly due to the deterioration in the structural quality of concrete (Arioz, 2007; Janotka et al., 2005; Sakr et al., 2005; Oktar et al., 1996). Under fire, hot surface layers of concrete lean to separate from cooler interior part of concrete and cracks are formed at the joints and in poorly compacted parts of concrete. When concrete is subjected to temperatures up to 600ºC, the results depend on the moisture condition, differences in stress acting upon, exposure duration and properties of aggregates (Neville, 2002). In addition, composition of cement and size of structural members affect the fire resistance of concrete (Poon et al., 2001; Husem, 2006).

Moisture content is one of the most important factors that affects the structural behavior of concrete at high temperatures (Lankard et al., 1971). According to Bingöl et al. (2008), when concrete specimens were heated at various temperatures, concrete's unit weight decreased due to the water released from the cement paste. Weight loss under high temperatures become more significant beyond 800ºC (Arioz, 2007). The change in mechanical properties can be also attributed to the moisture loss of concrete.

The type of aggregate also affects the behavior of concrete at high temperatures. Aggregates without silica shows lower strength loss at high temperatures (Neville, 2002). Furthermore, better fire resistance can be achieved when concrete has a low thermal conductivity such as lightweight concrete (Neville, 2002).

Sequence of heating and loading are also other factors affecting the residual strength of concrete. Besides, applied water in fire causes the enormous reduction in strength (Neville, 2002). Fast cooling method also resulted in further decrease in compressive strength than normal cooling (Chan et al., 1996; Nadeem et al., 2014). Cracking and crumbling of concrete occur due to CaO that turns into $Ca(OH)_2$ when water is used to stop fire (Akman, 2000).

Moreover, under high temperatures, substantial changes occur in chemical composition and physical structure of the concrete. Above 110ºC, chemically bound water significantly releases from the calcium silicate hydrate and micro-cracks initiate due to dehydration of hydrated calcium silicate and thermal expansion of aggregate from 300ºC (Arioz, 2007). In general, concrete's compressive strength maintained up to 300ºC (Mindess et al., 2003). According to Neville, (1981), below 250ºC, the impact of high temperature on strength is slight and irregular whereas significant strength losses occur above 300ºC. Dissociation of $Ca(OH)_2$ occurs at around 530ºC and results in the shrinkage of concrete (Arioz, 2007). Additionally, further disintegration of C-S-H gel occurs above 600ºC and concrete is crumbled at 800ºC (Hertz, 2005).

3.3 Stress- Strain Relation

Stress-strain of concrete is important in structural design. In general, when load is applied initially, concrete behaves nearly elastically and shows creep under continuous loading (Neville, 2002; Neville, 2008).

Stress- strain relationship of typical concrete in compression is non-linear and non-elastic. Stress-strain curvature and magnitude of strain depend on the rate of stress application. For example, at an extremely rapid application of load such as less than 0.01 sec, curvature becomes very small and the strain reduces significantly. When loading time increases from 5 sec. to 2 min, the strain can increase by up to 15% (Neville, 2008).

The curved stress-strain relationship occurs because of the ITZ between aggregate and cement paste and the formation of bond micro-cracks at the ITZ. Strain continuously increases with reduction in applied load and nominal applied stress. This is the part of curve where strain softening occurs. If material is brittle, curve ends suddenly at the peak. When descending part of curve becomes less steep, material has more ductile behavior (Neville, 2002).

3.4 Modulus of Elasticity

Properties of aggregate is an important factor affecting the modulus of elasticity. Although they do not have significant effects on the compressive strength, the elastic modulus of aggregate and the volumetric proportion of aggregate affect the modulus of elasticity. With an increase in elastic modulus of aggregate, concrete’s elastic modulus also increases (Neville, 2008). As it was stated before, the type of deformation produced in concrete partially depends on the elastic deformation of aggregate (Jones et al., 1971). According to Neville et al. (1983), elastic modulus was not affected by the curing, however, it was affected by the elastic modulus of coarse aggregate. Additionally, when aggregate has higher elastic modulus than cement paste, elastic modulus increases with a greater volume of aggregate (Neville, 2008).

Moisture condition is one of the factors which affects the elastic modulus. For example, elastic modulus of wet specimens is greater than that of dry one (Neville, 2008).

Moreover, at a given strength, elastic modulus is affected by the hydrated cement paste (Neville, 2002) and the shape of stress-strain curves also affects the static elastic modulus (Neville, 2008).

Bonding between aggregate and cement paste may also affect the elastic modulus (Neville et al. 1983). In the study of Senthil Kumar et al. (2015), in which HIPS were used instead of natural aggregates, the reason of reduction in elastic modulus was attributed to the weak bond between HIPS and cement paste.

3.6 Density

With the increase of aggregate density, the density of concrete increases at constant aggregate content (Neville, 2002). For this reason, when plastic aggregates were utilized to replace the conventional aggregates, the concrete/mortar density decreased with an increase in inclusion level (Ismail et al., 2008; Hannawi et al., 2010; Yang et al., 2015; Ozbakkaloglu et al., 2017).

3.7 Permeability

Permeability can be defined as the movement of liquids and gases easily through the concrete and it varies with the w/c and age of concrete (Neville, 2008). Permeability also depends on the size, shape, distribution and continuity of the pores (Neville, 2002). The coefficient of permeability decreases significantly when w/c decreases from 0.75 to 0.26 (Whiting, 1988).

The porosity of cement paste affects the permeability when concrete is made with normal weight aggregate. In addition, permeability becomes higher with the inclusion of more porous aggregate in concrete (Neville, 2008). At the same w/c, permeability of concrete and cement paste differs due to the permeability of aggregates. Aggregate with a very low permeability decreases the effective area of flow. Since the aggregate particles are surrounded by cement paste, the effect of aggregate content is low, and concrete’s permeability is greatly affected by the permeability of hardened cement paste (Neville, 2002).

Additionally, the properties of cement affect the permeability at constant w/c. For example, cement with coarse particles result in higher porosity than a finer cement (Hanaor et al. 1983). Therefore, when the strength of hardened cement paste increases, permeability decreases (Neville, 2002).

In addition, existence of larger capillary pores resulted in greater permeability of hydrated cement paste. w/c and degree of hydration affect the capillary pores and since the permeability is the general function of capillary pores, those parameters also affect the permeability of cement paste. For example, at low w/c (<0.6), capillaries are separated and not continuous, hence permeability becomes lower for a given degree of hydration. Moreover, permeability also decreases with a continuous hydration of the cement and with filling some of originally water filled space for a given w/c (Neville, 2008).

When moist curing is disrupted by a period of drying, permeability increases due to the creation of water passages as a result of the shrinkage cracks around the aggregates (Neville, 2008).

Therefore, in order achieve durability and low permeability, mixes should be produced with low w/c and well-graded aggregates should be used to produce dense concrete (Neville, 2008).

Chapter 4

MATERIALS AND EXPERIMENTAL PROCEDURE

4.1 Materials

4.1.1 Cement

The cement used in the experiment was CEM II/B-S 42.5 N type. The physical and chemical properties of the cement are provided in Table 1 and Table 2, respectively. The specific gravity and Blaine specific surface of cement were determined according to EN 196-6, and the initial setting time and Le Chatelier expansion were determined according to EN 196-3. In addition, EN 196-1 was used to determine compressive strength of cement and chemical composition of cement was obtained in accordance with EN 196-2.

Table 1: Physical properties of the CEM II/B-S 42.5 N type cement

Specific Gravity	**Specific Surface, Blaine (cm^2/g)**	**Initial Setting Time (min)**	**Le Chatelier Expansion (mm)**	**Compressive Strength (MPa)**		
				2-Day	**7- Day**	**28- Day**
3.04	3473	170	1	18.7	34.1	50.2

4.1.2 Marble Dust

Waste marble dust (MD) was obtained as a by-product of marble sawing and shaping from Akyürek Natural Marbler located in North Cyprus. The specific gravity of MD was 2.7. According to the sieve analysis of MD, there are also particles bigger than 2 mm. Approximately 43% of MD was finer than the 300 μm and 33% was passing through 180 µm. For this reason, MD finer than 300 µm was used in Part 1 experiments. Additionally, to be able to observe the effects of finer particles on the properties of concrete, MD finer than 180 µm was used in Part 2 experiments, respectively. X-Ray Diffraction (XRD) analysis of MD, its chemical composition and particle size distribution are given in Figure 1, Table 2 and Figure 2, respectively. According to the XRD result of MD, the material entirely consists of $CaCO_3$ (Calcite) crystals with no amorphous phase.

Table 2: Chemical composition of cement and MD

Oxide	**Cement (%)**	**MD (%)**
CaO	60.88	56.1
SiO_2	19.00	0.194
Al_2O_3	2.19	0.123
Fe_2O_3	2.89	0.0550
MgO	2.27	0.926
SO_3	2.55	0.0213
CaO free	1.00	-
Na_2O	-	0.0333
SrO	-	0.0221
P_2O_5	-	0.0189
K_20	-	0.0181
Loss on ignition	0.98	42.5
Insoluble residue	0.02	-

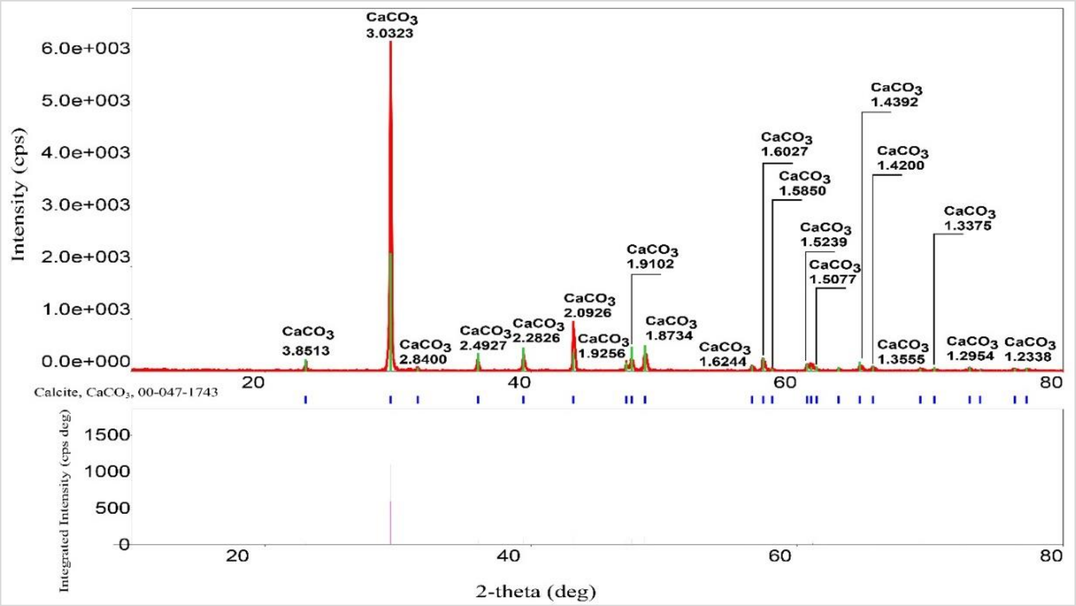


Figure 1: XRD analysis of MD

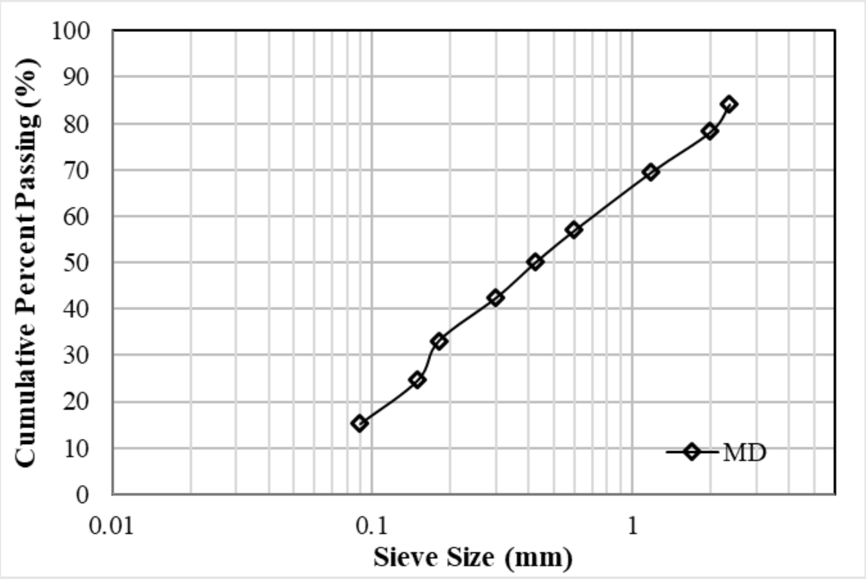


Figure 2: Particle size distribution of MD

4.1.3 Waste Electronic Plastics

The shredded waste electronic plastics (e-plastic) obtained from waste computers and the keyboards were supplied by a factory in Haspolat, North Cyprus. Following the removal of the impurities, e-plastics were separated into different size fractions by mechanical sieving. The grading is presented in Figure 3 and different size fractions of e-plastics are given in Figure 4a-c. The specific gravity of the e-plastic was 1.07 and maximum size of the fractions was 14 mm. Thermal gravimetric analysis (TGA) and Differential scanning calorimetry (DSC) analysis of e-plastic are also given in Figure 5 and Figure 6, respectively.

4.1.4 Fine and Coarse Aggregates

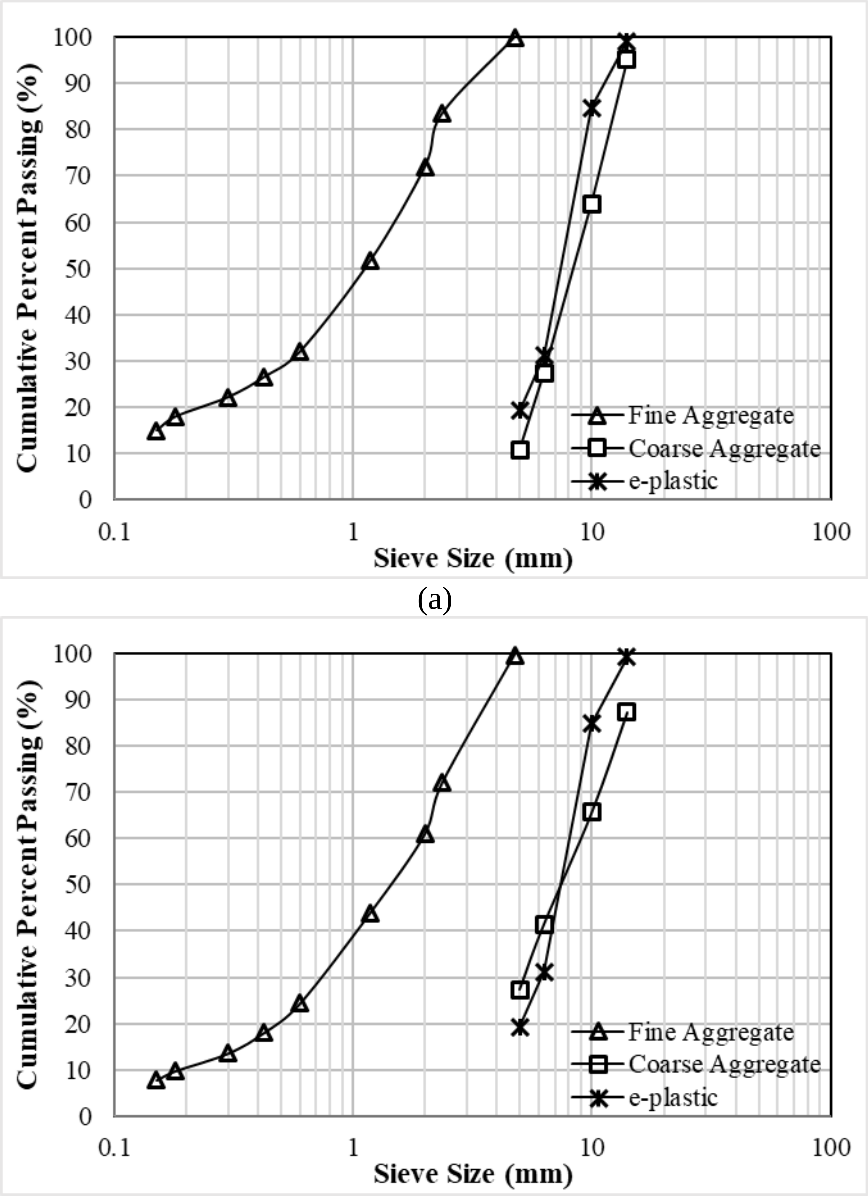
The fine aggregate was a river sand with a maximum size of 5 mm. Its specific gravity was 2.73. The coarse aggregate was a crushed type with a maximum size of 14 mm and with a specific gravity of 2.70. The particle size distributions of the fine and coarse aggregates were determined according to ASTM C136/C136M-19 and given in Figure 3 for Part 1 and Part 2 experiments.

4.1.5 Mixing Water

Tap water was used during the preparation of concrete specimens.

4.1.6 Superplasticizer

A Master Glenium 27 High Range Water Reducing Superplasticizer Admixture (EN934-2:T3.1/3.2) was used to keep the slump within the range of 180 mm to 220 mm in the concrete mixtures. Superplasticizer was added by weight of cement. At each e-plastic replacement level, superplasticizer content was changed to achieve workability within the range of 180-220 mm.



(b)

Figure 3: Particle size distribution of fine aggregates, coarse aggregates and e-plastics; (a) Part 1 experiments, (b) Part 2 experiments

(a) (b) (c)

Figure 4: Size fractions of e-plastic particles; (a) 0-5 mm, (b) 5-10 mm, (c) 10-14 mm

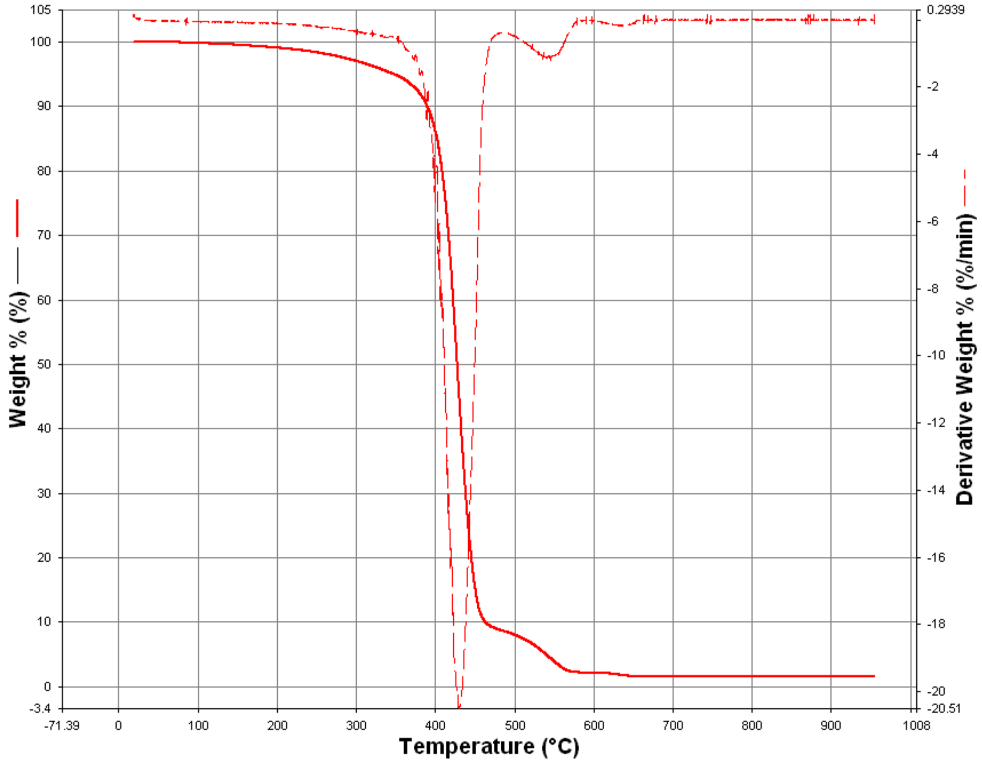


Figure 5: TGA analysis of e-plastic

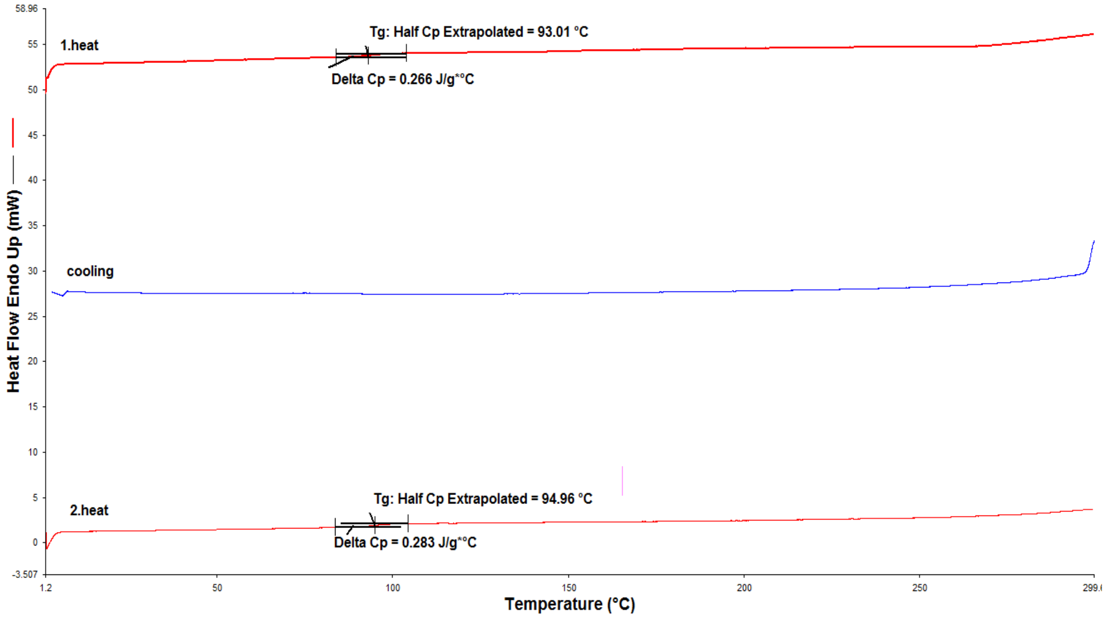


Figure 6: DSC analysis of e-plastic

4.2 Experimental Procedure

Mixing processes were kept constant for all mixtures. Concrete mixtures were designed with a constant w/c of 0.40. The slump value of the mixtures was kept within the range of 180 to 220 mm by using the superplasticizer admixture. Superplasticizer amount was different for different e-plastic replacement levels since the replacement of natural aggregates with e-plastic particles affect the workability of concrete. Therefore, superplasticizer content changed with e-plastic replacement level to achieve required slump range. MD was used as an additive and/or filler material at the proportions ranging from 0% to 15% by weight of cement in concrete and shredded e-plastic particles were incorporated by replacing 0%, 10%, 20%, 30% and 40% of the aggregates (both fine and coarse) by volume. According to the sieve analysis undertaken (Figure 3), the particle size distribution of the e-plastics used was mostly in the range of 5-10 mm. In e-plastics aggregate-bearing mixtures, 70%, 20% and 10% by volume of 5-10 mm, 10-14 mm and 0-5 mm size fractions of natural aggregates were substituted with corresponding e-plastic particles, respectively.

In order to eliminate the segregation risk during and after mixing, e-plastic particles were introduced after all ingredients were added into the mixer and before the addition of mixing water. After mixing, concrete specimens were cast into 100 mm cubic, 150 mm cubic, and 100x200 mm cylindrical and 100x100x500 mm prismatic moulds with 10 to 15 seconds vibration. After that, all specimens were kept in a moist curing room at 24 $\pm 2^0$C and 95% relative humidity for 24 hours. Then, they were demoulded and transferred to a water tank for 28 days curing before testing.

4.2.1 Part 1 Experiments

17 concrete mixes incorporated with four different proportions of MD finer than 300 μm (0%, 5%, 10%, and 15%), and five different proportions of e-plastics (0%, 10%, 20%, 30% and 40%) were prepared, as shown in Table 3**.** The mix proportions for the concrete were determined according to the BRE Method and given in Appendix A. As it was mentioned above, 70%, 20% and 10% by volume of 5-10 mm, 10-14 mm and 0-5 mm size fractions of natural aggregates were substituted with corresponding e-plastic particles, respectively. The details of the mix design calculations are given in Appendix A.

4.2.1.1 Compressive Strength

The compressive strength of the mixtures was determined in accordance with ASTM C39/C39M-18 standard. 100 mm cube specimens were tested by using a 3000 kN capacity compressive universal testing machine.

4.2.1.2 Unit Weight

100x200 mm cylinders were used to obtain the dry unit weight of the concrete mixtures.

4.2.1.3 Splitting Tensile Strength

Splitting tensile strength of the mixtures was determined by using 100x200 mm cylinders in accordance with the ASTM C496/C496M-17.

4.2.1.4 Modulus of Elasticity

Elastic modulus of 100x200 mm cylindrical concrete specimens were determined according to the ASTM C469/C469M–14. Specimens were loaded up to the 40% of the ultimate load. Longitudinal strain produced by 40% of ultimate load and stress corresponding to a longitudinal strain of 0.00005 were determined and chord modulus of elasticity was calculated according to the formula proposed by the standard. The formula is given in the equation below:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050} \tag{1}$$

where:

E= chord modulus of elasticity, MPa,

S_1= stress corresponding to a longitudinal strain, ε_1, of 50 millionths, MPa,

S_2= stress corresponding to 40% of ultimate load, MPa,

ε_2= longitudinal strain produced by stress S_2.

4.2.1.5 Load- Deformation Curves

100x200 mm cylinder specimens were used to determine the load-deformation curves under compression (at a constant strain rate of 0.3 mm/min) as shown in Figure 7. From the obtained load- deformation curves, stress- strain diagrams were determined and toughness was calculated from the area under the stress- strain curve by applying the equation 2.

$$\left[(\varepsilon_1 - \varepsilon_0)\, x \left(\frac{\sigma_0+\sigma_1}{2}\right)\right] + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \left[(\varepsilon_n - \varepsilon_{n-1})\, x \left(\frac{\sigma_{n-1}+\sigma_n}{2}\right)\right] \qquad (2)$$

where:

ε= strain,

σ = stress, MPa

P40M15, Specimen 1 is given as an example in the Appendix B.

Figure 7: Load- deformation test under compression

4.2.1.6 Water Penetration Depth

150 mm cubic specimens were used to test the water penetration depth in accordance with BS EN 12390-8:2000. The specimens were kept under pressure for 72 hours and the depth of water penetration was measured on the split surface of the test specimens.

The results reported for each test are the average of three specimens.

Table 3: Materials and proportions of concrete mixtures

Mixture	Cement (kg/m^3)	MD (%)	Water (kg/m^3)	SP (%)	Natural Aggregate (kg/m^3)			e-plastic Aggregate (kg/m^3)		
					0-5 (mm)	5-10 (mm)	10-14 (mm)	0-5 (mm)	5-10 (mm)	10-14 (mm)
P0M0	430	0	172	1.25	971.59	443.21	443.21	-	-	-
P10M0	430	0	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P10M5	430	5	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P10M10	430	10	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P10M15	430	15	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P20M0	430	0	172	0.70	952.16	381.16	425.48	7.70	24.59	7.03
P20M5	430	5	172	0.70	952.16	381.16	425.48	7.70	24.59	7.03
P20M10	430	10	172	0.70	952.16	381.16	425.48	7.70	24.59	7.03
P20M15	430	15	172	0.70	952.16	381.16	425.48	7.70	24.59	7.03
P30M0	430	0	172	0.50	942.44	350.14	416.62	11.55	36.88	10.54
P30M5	430	5	172	0.50	942.44	350.14	416.62	11.55	36.88	10.54
P30M10	430	10	172	0.50	942.44	350.14	416.62	11.55	36.88	10.54
P30M15	430	15	172	0.50	942.44	350.14	416.62	11.55	36.88	10.54
P40M0	430	0	172	0.45	932.73	319.11	407.75	15.40	49.18	14.05
P40M5	430	5	172	0.45	932.73	319.11	407.75	15.40	49.18	14.05
P40M10	430	10	172	0.45	932.73	319.11	407.75	15.40	49.18	14.05
P40M15	430	15	172	0.45	932.73	319.11	407.75	15.40	49.18	14.05

4.2.2 Part 2 Experiments

As shown in Table 4, ten concrete mixes incorporated with two different proportions of MD finer than 180 μm (0% and 15%) and five different proportions of e-plastics (0%, 10%, 20%, 30% and 40%) were prepared. The mix proportions for the concrete were determined according to the BRE Method.

4.2.2.1 Flexural Strength

The flexural strength of 100x100x500 mm prismatic specimens was determined in accordance with ASTM C78/78M-18.

4.2.2.2 Flexural Toughness

100x100x500 mm prismatic specimens with the span length of 300 mm and load distance of 100 mm were used to perform the test according to the ASTM C1609/1609M- 19a, as shown in Figure 8. Then, area under the load-deflection curve was determined for each concrete specimen.

Figure 8: Flexural toughness test

4.2.2.3 Unit Weight at Ambient and High Temperatures

100 mm cubes were used to determine the unit weight. 100 mm cubes were exposed to high temperatures of 60ºC, 100ºC and 200ºC. The exposure temperatures were determined based on the following considerations: 60ºC is the extreme weather conditions in summer, 100ºC is the approximate glass transition temperature of e-plastic that was obtained from the DSC analysis given in Figure 6. Additionally, at and above 100ºC, a large number of cracks form inside the concrete due to high inner pressure caused by water vapor (Phan et al., 2001), and 200ºC is the maximum

temperature within the laboratory limitations. After reaching the required temperature, the specimens were heated for 2 hours at each temperature. Heating rate was 6ºC/min. After that, concrete specimens were cooled down to room temperature in laboratory conditions and weight loss under high temperatures were investigated.

4.2.2.4 Compressive Strength at Ambient and High Temperatures

100 mm cubes were used to determine the compressive strength of the mixtures in accordance with ASTM C39/C39M-18 standard. After specimens were subjected to temperatures of 60ºC, 100ºC and 200ºC for 2 hours and cooled to room temperature, concretes’ compressive strength at ambient and high temperatures was determined after 1 day of cooling. Therefore, compressive strength loss under high temperatures was investigated.

4.2.2.5 Surface Condition of Concrete Specimens under High Temperatures

In addition to the investigations on the unit weight loss and compressive strength loss under high temperatures, surface conditions of concrete specimens were also tested at the temperature of 60ºC, 100ºC and 200ºC. Additionally, another furnace was used to observe the effect of 300ºC on the surface condition of concrete.

The results reported for each test are the average of three specimens.

Table 4: Materials and proportions of concrete mixtures

Mixture	**Cement (kg/m^3)**	**MD (%)**	**Water (kg/m^3)**	**SP (%)**	**Natural Aggregate (kg/m^3)**			**e-plastic Aggregate (kg/m^3)**		
					0-5 (mm)	**5-10 (mm)**	**10-14 (mm)**	**0-5 (mm)**	**5-10 (mm)**	**10-14 (mm)**
P0M0	430	0	172	1.25	971.59	443.21	443.21	-	-	-
P0M15	430	15	172	1.25	971.59	443.21	443.21	-	-	-
P10M0	430	0	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P10M15	430	15	172	1.05	961.87	412.19	434.35	3.85	12.29	3.51
P20M0	430	0	172	0.9	952.16	381.16	425.48	7.70	24.59	7.03
P20M15	430	15	172	0.9	952.16	381.16	425.48	7.70	24.59	7.03
P30M0	430	0	172	0.9	942.44	350.14	416.62	11.55	36.88	10.54
P30M15	430	15	172	0.9	942.44	350.14	416.62	11.55	36.88	10.54
P40M0	430	0	172	0.9	932.73	319.11	407.75	15.40	49.18	14.05
P40M15	430	15	172	0.9	932.73	319.11	407.75	15.40	49.18	14.05

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Part 1 Experiments

5.1.1 Workability

Slump values of all concrete mixtures are given in Figure 9. Concrete mixtures with a constant w/c were designed and the slump value of the mixtures was kept within the range of 200±20 mm by using a superplasticizer admixture. With an increase in the e-plastic replacement level, superplasticizer amount decreased to achieve the required slump range due to almost zero water absorption capacity and smooth surface texture of e-plastics. Slump of concrete mixtures with e-plastics and without MD was around 220 mm at all replacement levels. However, addition of MD up to 15% at each e-plastic replacement level decreased the slump value slightly.

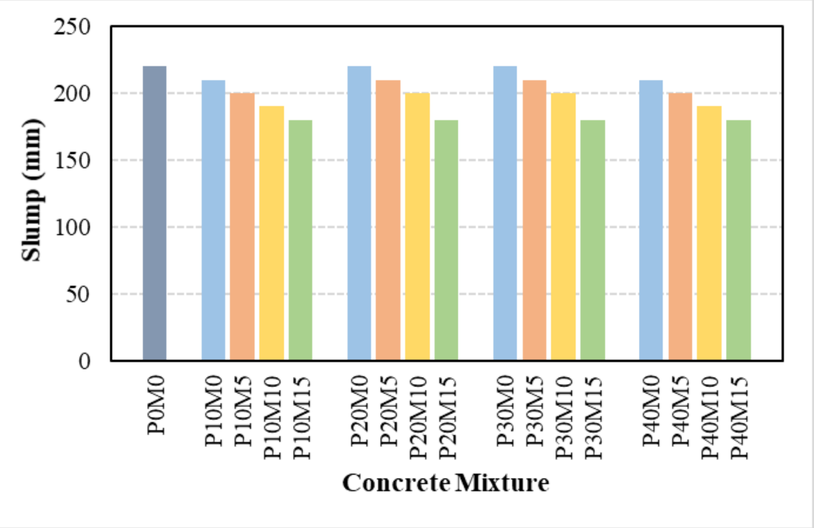


Figure 9: Slump values of concrete mixtures

5.1.2 Dry Unit Weight

Figure 10 and Table 5 show the dry unit weight of the concrete specimens at 28-day age. The dry unit weight of concrete containing e-plastic aggregate decreased as the replacement ratio increased. The results obtained were consistent with the literature (Rahmani et al., 2013; Albano et al., 2009). The highest decrease of 10% and lowest decrease of 2% were observed at 40% and 10% replacement ratios, respectively, compared to that of the control mixture. With the addition of MD, the dry unit weight increased between 1.6% and 3.5%.

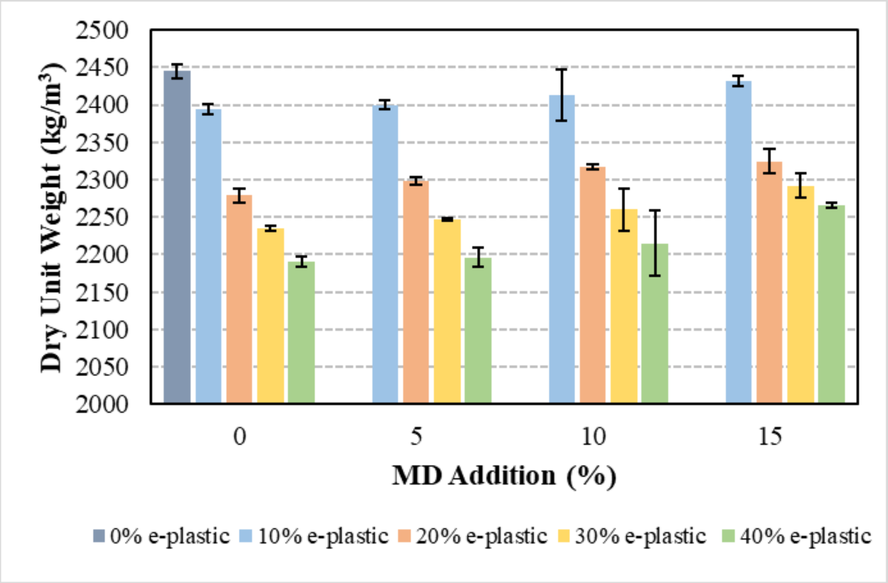


Figure 10: Dry unit weight of concrete mixtures

Table 5: Mass and dry unit weight of concrete specimens

Mixture	Mass (kg)				Unit Weight (kg/m^3)
	1	**2**	**3**	**Average**	**Average**
P0M0	3.85	3.85	3.82	3.84	2445
P10M0	3.77	3.75	3.77	3.76	2394
P20M0	3.59	3.60	3.57	3.58	2279
P30M0	3.50	3.51	3.51	3.51	2235
P40M0	3.43	3.44	3.45	3.44	2190
P10M5	3.79	3.77	3.77	3.77	2400
P20M5	3.62	3.61	3.61	3.61	2298
P30M5	3.53	3.53	3.53	3.53	2247
P40M5	3.44	3.44	3.48	3.45	2196
P10M10	3.81	3.73	3.83	3.79	2413
P20M10	3.64	3.65	3.65	3.64	2317
P30M10	3.61	3.53	3.53	3.55	2260
P40M10	3.44	3.45	3.56	3.48	2215
P10M15	3.83	3.82	3.81	3.82	2432
P20M15	3.66	3.68	3.63	3.65	2324
P30M15	3.63	3.58	3.59	3.60	2292
P40M15	3.57	3.56	3.56	3.56	2266

5.1.3 Compressive Strength

Aggregate properties (type, size, shape, grading and surface texture), mix proportions and w/c are the main factors that affect the compressive strength of concrete. Figure 11 and Table 6 show the 28-day compressive strength values for all specimens produced with different proportions of e-plastic aggregate substitutions and MD additions.

From Figure 11, it can be observed that the incorporation of e-plastic into concrete reduced the compressive strength compared to that of the control mixture. Strength decreased by 18%, 13%, 30% and 36% at 10%, 20%, 30% and 40% e-plastic replacement level at 0% MD addition compared to that of control concrete. There was a slight increase in the compressive strength of the e-plastic aggregate-bearing mixtures with the presence and increase of MD content. However, all compressive strength values were still less than that of the control mixture.

Regardless of the amount of MD added, at 20% e-plastic substitution level, the least reduction in compressive strength occurred. Compared to that of the control mixture, the maximum reduction in compressive strength was 36% (in P40M0 mixture), and the minimum reduction (8%) was found in P20M15. Similar results were reported by Hannawi et al. (2010) and Yang et al. (2015). They stated that the decrease in concrete compressive strength was not proportional to the recycled plastic aggregate replacement level. In this study, when the replacement level was increased from 10 to 20%, the decrement in the compressive strength reduced, however, at 30 and 40% replacement levels, the decrement increased again. Compressive strength loss at 20% replacement level is significantly lower than the strength reductions reported previously in concretes incorporating fine plastics (i.e., 72%) (Batayneh et al., 2007) and recycled fine PP (i.e., 32.3%) (Akinyele et al., 2018). Additionally, reductions at 10% and 20% replacement levels were found to be lower than that obtained by Akram et al. (2015) at 15% replacement of coarse aggregates (i.e., 34%). The decrement in concrete’s compressive strength containing 30% and 40% e-plastic was found to be about twice of that of concretes produced with 10% and 20% e-plastic replacement levels, respectively. This may be attributed to that some voids in concrete can be filled with fine plastic particles at lower replacement levels as it was also stated by Yang et al. (2015). However, high volumes of free water may be accumulated around plastic particles at higher replacement levels due to almost zero water absorption of plastics resulting in a relatively weak bond between e-plastic aggregate and matrix (Frigione, 2010; Saikia et al., 2014; Yang et al., 2015).

Furthermore, the decrease in compressive strength could be attributed to the lower elastic modulus and strength of e-plastic aggregates than that of natural aggregates, as was presented by Zaleska et al. (2018). The smooth surface of plastic aggregates also prevents the formation of a strong bond between cement paste and plastic aggregate (Rahmani et al., 2013). However, MD addition developed the concrete compressive strength and partially compensated for the negative effect of the presence of e-plastic aggregate due to its filler effect in concrete. When the MD content increased from 0 to 15%, the compressive strength of the concrete increased by 7%, 7%, 15% and 12% at 10%, 20%, 30% and 40% e-plastic inclusion levels. Therefore, the addition of 15% MD increased the compressive strength between 7% and 15% when compared with the concrete mixtures including e-plastics but not MD (P10M0, P20M0, P30M0, and P40M0). MD is not a pozzolanic material however, it acts as an inert filler material. It was stated that (Topçu et al., 2009; Corinaldesi et al., 2010) the usage of MD as a mineral admixture in concrete or mortar increases the compressive strength at a constant workability. Additionally, since the coarser sizes of plastic particles may result in the reduction in the packing level of concrete (Sadrmomtazi et al., 2016), use of MD may improve the particle packing of concrete. In another study, positive effect of MD on binding capacity of the cement was mentioned. Calcite in MD interacts with C_3A during the hydration of cement to form carbo-aluminate and resulting in a higher strength (Munir et al., 2017). According to XRD analysis of the MD used in these experiments, calcite was found to be the main crystalline ingredient of MD. This may be one of the reasons of the positive effect of MD on the compressive strength of concrete.

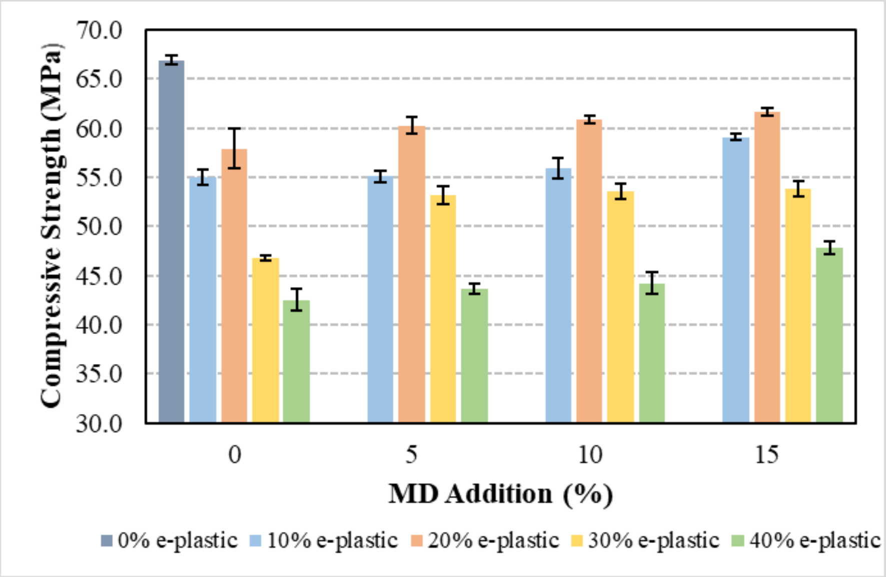


Figure 11: Effect of e-plastic aggregate inclusion and MD addition on 28 day-compressive strength of HSC

Table 6: Compressive strength of concrete specimens

Mixture	Compressive Strength (MPa)			
	1	2	3	Average
P0M0	67.3	66.4	66.9	66.9
P10M0	55.8	54.9	54.3	55.0
P10M5	54.9	55.8	54.6	55.1
P10M10	55.8	55.0	57.0	55.9
P10M15	59.4	59.1	58.8	59.1
P20M0	59.1	55.6	59.1	57.9
P20M5	61.2	59.5	60.1	60.3
P20M10	60.5	60.9	61.3	60.9
P20M15	62.1	61.4	61.6	61.7
P30M0	46.5	47.0	46.7	46.7
P30M5	52.1	53.8	53.6	53.2
P30M10	52.7	53.7	54.3	53.6
P30M15	54.2	52.9	54.4	53.8
P40M0	43.8	42.0	41.8	42.5
P40M5	43.9	43.1	44.0	43.7
P40M10	45.5	43.8	43.4	44.2
P40M15	47.4	48.6	47.5	47.8

5.1.4 Splitting Tensile Strength

The 28 day-splitting tensile strengths of the mixtures are shown in Figure 12 and Table 7. From Figure 12, it is clear that the splitting tensile strength of all concrete mixes containing e-plastic aggregate was lower than that of the control concrete. However, irrespective of the e-plastic aggregate substitution level, the tensile strength of the concrete was improved by MD addition at all ratios.

Compared to the control concrete, the reductions in splitting tensile strength at 10%, 20%, 30% and 40% e-plastic aggregate inclusion levels and 0% MD addition, were 11%, 14%, 15% and 21%, respectively. Splitting tensile strength is affected by the properties of ITZ (Saikia et al., 2012). Therefore, the reduction in splitting tensile strength of concrete could be explained by the weak bond between the smooth surface of e-plastic and cement paste. At 20% replacement level, reduction in splitting tensile (i.e., 14%) is lower than the strength reduction reported previously in concrete incorporating fine PET (i.e., 15.9% and 18.06%) for the w/c ratios 0.42 and 0.54 respectively, at 15% replacement level (Rahmani et al., 2013). Additionally, reduction at 30% replacement level was lower than that obtained by Ozbakkaloglu et al. (2017) in which coarse PP was used to replace natural aggregates in HSC mixes (i.e., 20.3%). Studies showed that the shape of plastics also affect splitting tensile strength. According to Gu et al. (2016), irregular shaped plastics decrease splitting tensile strength significantly than regular shaped plastics. However, at 15% MD addition, the loss in tensile strength was relatively lower; i.e., it was 1%, 5%, 7% and 11% for 10%, 20%, 30%, and 40% e-plastic substitutions, respectively. In general, the tensile strength of concrete decreased with the e-plastic substitution level; thus, the fact was more pronounced at 40% replacement level. On the other hand, the higher the MD addition, the lower the reduction in concrete tensile strength upon e-plastic aggregate inclusion, meaning that at 15% MD addition, the tensile strengths of the e-plastic aggregate-containing mixtures approached that of the control concrete. Compared to that of the control mixture, the maximum (21%) and minimum (1%) reduction in split tensile strength occurred in P40M0 and P10M15, respectively. It is important to note that the reduction in splitting tensile strength was lower than the decrease in compressive strength due to e-plastic substitution and MD addition. This may have occurred due to the ductile behaviour of e-plastics and the increased ductility of concrete with e-plastic addition.

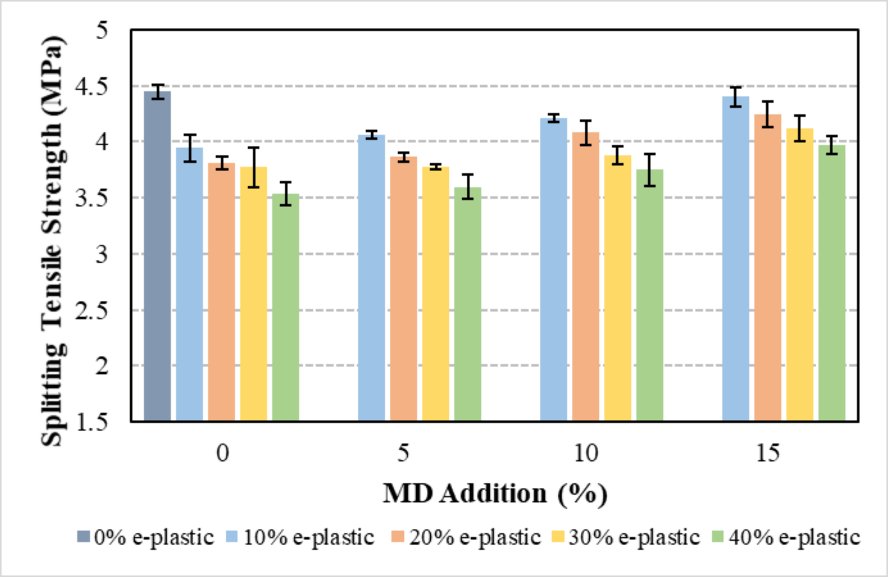


Figure 12: Effect of e-plastic aggregate inclusion and MD addition on 28 day-splitting tensile strength of HSC

Table 7: Splitting tensile strength of concrete specimens

Mixture	Splitting Tensile Strength (MPa)			
	1	2	3	Average
P0M0	4.38	4.50	4.46	4.45
P10M0	4.06	3.95	3.82	3.94
P10M5	4.06	4.10	4.03	4.07
P10M10	4.25	4.19	4.18	4.21
P10M15	4.32	4.39	4.49	4.40
P20M0	3.76	3.87	3.80	3.81
P20M5	3.91	3.83	3.85	3.86
P20M10	3.95	4.16	4.13	4.08
P20M15	4.13	4.36	4.24	4.24
P30M0	3.96	3.60	3.75	3.77
P30M5	3.76	3.78	3.81	3.78
P30M10	3.78	3.92	3.93	3.88
P30M15	3.99	4.20	4.18	4.12
P40M0	3.46	3.66	3.49	3.53
P40M5	3.48	3.62	3.69	3.60
P40M10	3.91	3.71	3.63	3.75
P40M15	4.04	4.00	3.88	3.97

As shown in Figure 13, the weak bond between e-plastic and matrix manifested itself by the de-bonding of plastic particles from matrix, but not failing during the split tension test. The reason for this was attributed to the smooth surfaces and low strength of e-plastic aggregates. Additionally, the accumulation of bleeding water at the surface of e-plastics may further weaken the ITZ.

Figure 13: Concrete specimens with e-plastic after splitting tensile strength test

5.1.5 Modulus of Elasticity

The modulus of elasticity of concrete specimens obtained at the age of 28 days are shown in Figure 14 and Table 8. When the e-plastic aggregate replacement ratios increased, the elastic modulus of the concrete decreased since e-plastics have lower density than natural aggregates. The elastic modulus of the control concrete was 41 GPa and decreased by 7%, 15%, 24% and 29% at 10%, 20%, 30% and 40% e-plastic replacement levels, respectively. This observation is in agreement with previous findings on concrete or mortar including different types of waste plastic aggregates (Hannawi et al., 2010; Rahmani et al., 2010; Senthil Kumar et al., 2015). Slight changes were observed with the addition of 15% MD at 20%, 30% and 40% e-plastic replacement levels. The reductions in modulus of elasticity were found to be 12%, 20% and 22% when 15% MD was used as an additive at 20%, 30% and 40% e-plastic replacement levels compared to the that control concrete (P0M0). Concrete elastic modulus depends on the elastic moduli of ingredients, their volumetric proportions and the bond between aggregate and matrix (Neville, 2002).

The type of aggregate also affects the modulus of elasticity of concrete because the type of deformation produced in concrete partially depends on the elastic deformation of aggregate (Jones et al., 1971; Saikia et al., 2012). Additionally, the stronger the bond between aggregate and matrix, the more stress transfer between them, resulting in a higher modulus of elasticity. The elastic modulus test results supported this fact, so that with the increase in e-plastic aggregate replacement, the elastic modulus decreased at all replacement levels due to the poor bond between e-plastic and cement matrix.

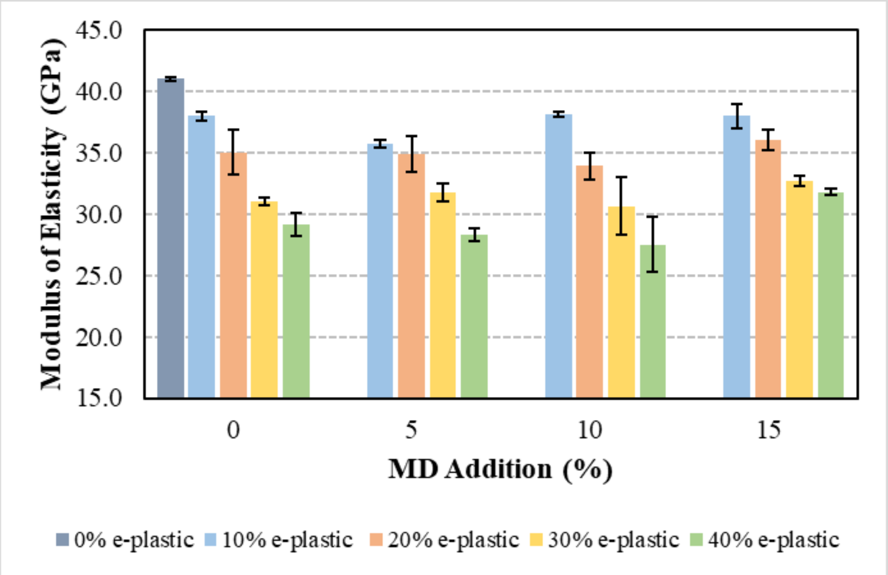


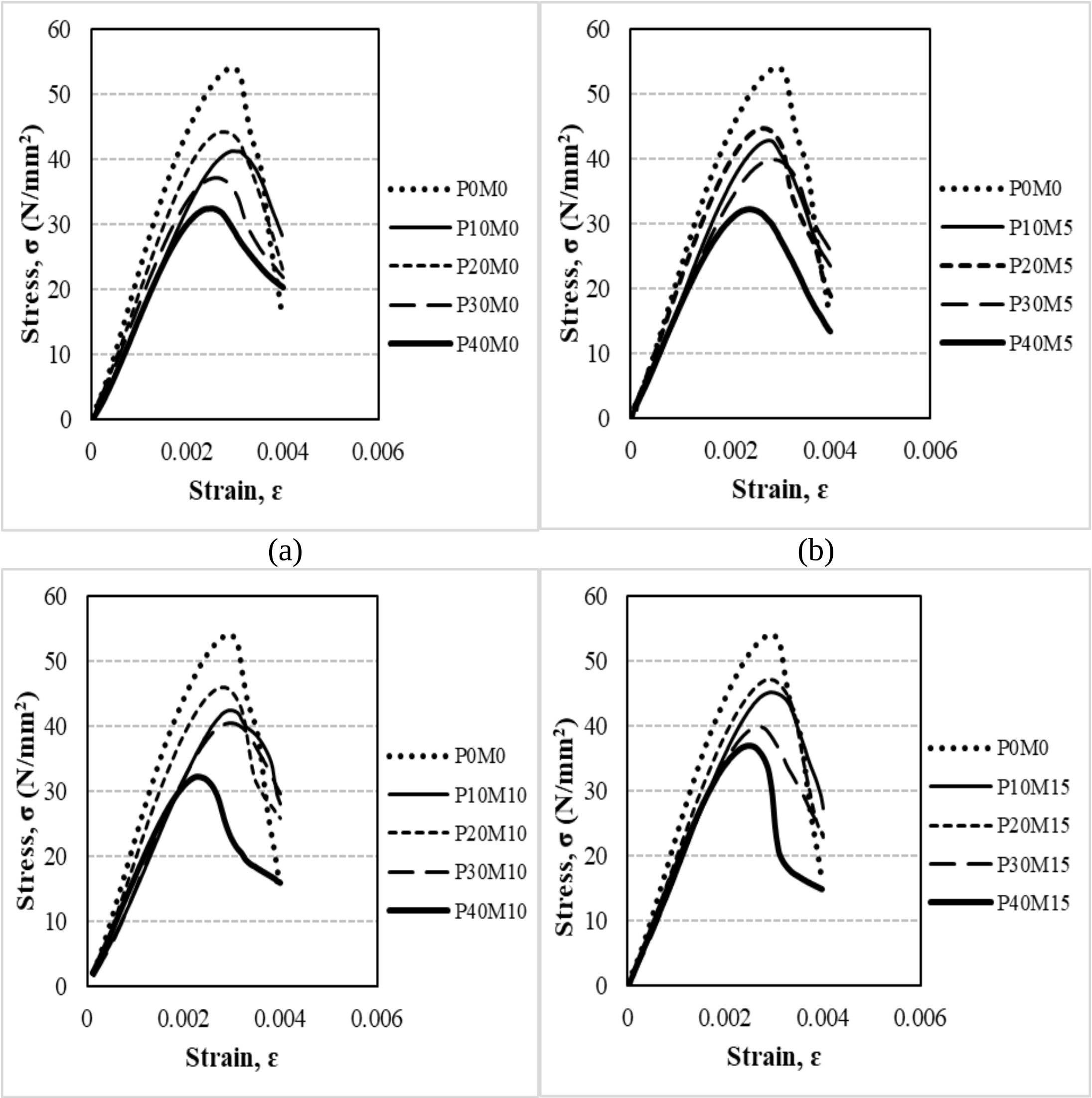
Figure 14: Effect of e-plastic aggregate inclusion and MD addition on the 28 day-modulus of elasticity of HSC

Table 8: Modulus of elasticity of concrete specimens

Mixture	**Modulus of Elasticity (GPa)**			
	1	**2**	**3**	**Average**
P0M0	40.8	41.2	41.0	41.0
P10M0	38.3	37.6	38.1	38.0
P10M5	35.7	36.0	35.4	35.7
P10M10	38.3	37.9	38.1	38.1
P10M15	38.9	38.1	36.9	38.0
P20M0	32.9	36.1	36.0	35.0
P20M5	35.3	36.1	33.3	34.9
P20M10	34.0	32.8	35.0	33.9
P20M15	36.9	35.3	35.8	36.0
P30M0	31.3	30.7	31.0	31.0
P30M5	32.0	32.3	30.9	31.7
P30M10	33.3	29.7	28.9	30.6
P30M15	32.7	33.1	32.3	32.7
P40M0	30.0	28.1	29.4	29.2
P40M5	28.8	27.8	28.4	28.3
P40M10	28.7	24.9	28.9	27.5
P40M15	31.5	32.0	31.9	31.8

5.1.6 Stress-Strain Relationship

The stress-strain curves of 28 days 100x200 mm cylindrical concrete specimens under compression are shown in Figure 15a-d. It can be clearly seen from these figures that, irrespective of the e-plastic aggregate replacement level, the ultimate strength was lower than that of the control concrete. The highest decrease in compressive strength was observed at 40% and the lowest reduction at 20% e-plastic aggregate-bearing mixture, regardless of the level of MD addition. However, at 10%, 20% and 30% e-plastic aggregate replacement ratios at all MD addition proportions, the stresses corresponding to the 0.004 strain were higher than that of the control concrete. The descending part of the σ-ε diagram of the control concrete was steeper than those of the mixtures containing e-plastic aggregate. Therefore, it can be concluded that the mixtures with e-plastics were more ductile than the control concrete, as theoretically stated by Neville (2002).



(a) (b)

(c) (d)

Figure 15: Effect of e-plastic aggregate inclusion and MD addition (a) at 0%, (b) at 5%, (c) at 10%, (d) at 15% on concrete stress-strain relationship

5.1.7 Toughness

Toughness values of the concrete mixtures were calculated from the area under their stress-strain curves**.** It can be seen from Figure 16 that the incorporation of both e-plastic and MD into concrete reduced the toughness when compared with that of the control mixture. In general, e-plastic aggregate inclusion reduced the concrete toughness considerably; however, with the addition of MD, there was a slight increase in the toughness of the mixtures.

Regardless of the amount of MD addition, mixtures with 20% e-plastic aggregate were the most successful in terms of toughness, and showed the closest toughness values to that of the control concrete. The slightly higher toughness of mixtures containing 20% e-plastic than 10% and 30% e-plastic-bearing mixtures was attributed to either higher ultimate strength or less steep character of post-peak portion of stress-strain diagram of the former mixture. It can be noted that these mixtures had the highest compressive strength among the test mixtures. Moreover, compared to the toughness of the control mixture, the maximum (39%) and minimum (6%) reductions in toughness were recorded in the P40M10 and P20M15 mixtures, respectively.

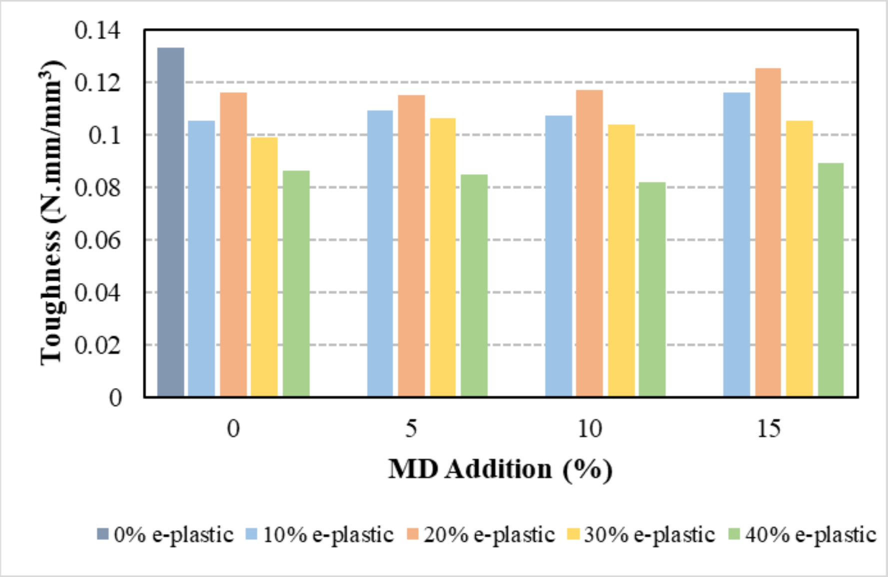


Figure 16: Effect of e-plastic aggregate inclusion and MD addition on toughness of HSC

5.1.8 Permeability

Figure 17 and Table 9 shows the effect of e-plastic aggregate inclusion and MD addition on the concrete water penetration depth. Water penetration depth decreased by 19% (P10M0) but increased by 28% (P20M0), 32% (P30M0) and 55% (P40M0) compared to that of the control concrete. It can be seen from the results that the mixtures containing 10% e-plastic aggregate, either with or without MD, had somewhat lower water penetration depths than the control mixture. Voids may be filled with fine e-plastic particles at lower replacement levels as it was also stated by Safi et al. (2013). However, increase in water penetration depth with an increase in the e-plastic aggregate replacement level may be due to the weak ITZ between the matrix and plastic aggregate. At higher replacement levels, especially coarser e-plastic aggregates may increase the porosity. Plane shape of e-plastic is also another factor affecting the permeability as it was also stated by Albano et al. (2009). Similarly, Hannawi et al. (2010) found that mortar porosity and permeability increased at high plastic aggregate contents.

On the other hand, MD as an additive, had no significant effect on depth of penetration in mixtures containing 10% e-plastic aggregate. However, as MD increased from 0 to 15% at 20%, 30% and 40% in the e-plastic aggregate mixtures, its positive effect on impermeability became clear. Water penetration depth decreased by 33%, 29% and 35% in the 20%, 30% and 40% e-plastic aggregate mixtures with 15% MD compared to those of the corresponding concretes containing no MD. The reason may be attributed to that MD could improve particle packing and decreases the permeability. Additionally, it was reported previously that when MD was used in concrete to partially replace fine aggregate, an increase in the MD percentage from 5 to 15% significantly decreased the water penetration depth due to the densification of ITZ arisen from water absorption of MD (Binici et al., 2007).

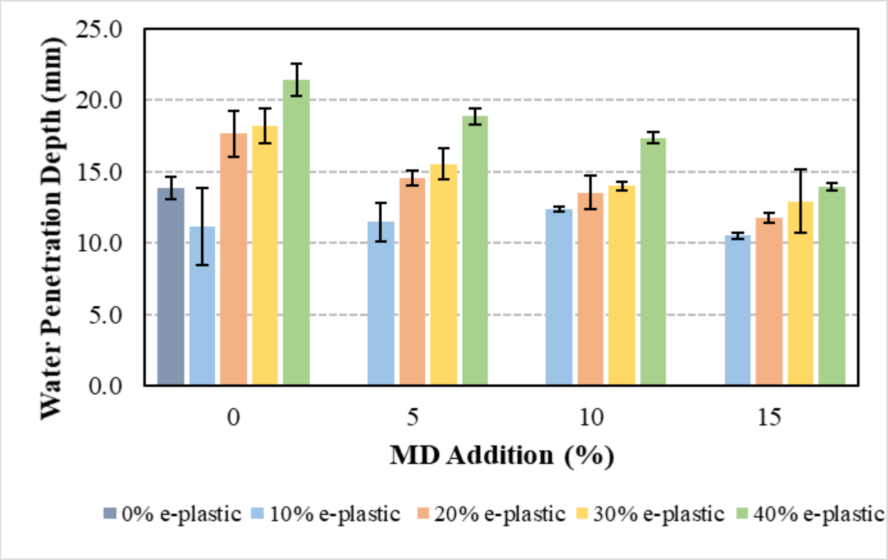


Figure 17: Effect of e-plastic aggregate inclusion and MD addition on concrete water penetration depth

Table 9: Water penetration depth of concrete specimens

Mixture	Water Penetration Depth (mm)			
	1	2	3	Average
P0M0	14.0	13.0	14.5	13.8
P10M0	9.2	10.0	14.3	11.2
P10M5	11.4	12.8	10.2	11.5
P10M10	12.4	12.3	12.6	12.4
P10M15	10.6	10.7	10.3	10.5
P20M0	16.8	19.5	16.7	17.6
P20M5	14.0	14.7	15.0	14.6
P20M10	12.6	14.8	13.1	13.5
P20M15	11.4	12.1	11.8	11.8
P30M0	17.1	19.5	18.0	18.2
P30M5	15.7	16.5	14.4	15.5
P30M10	14.0	14.3	13.7	14.0
P30M15	11.8	11.4	15.5	12.9
P40M0	21.7	20.1	22.4	21.4
P40M5	19.3	18.3	19.0	18.9
P40M10	17.5	16.9	17.7	17.4
P40M15	13.7	14.2	13.9	13.9

5.1.9 Relationship between Compressive Strength and Modulus of Elasticity

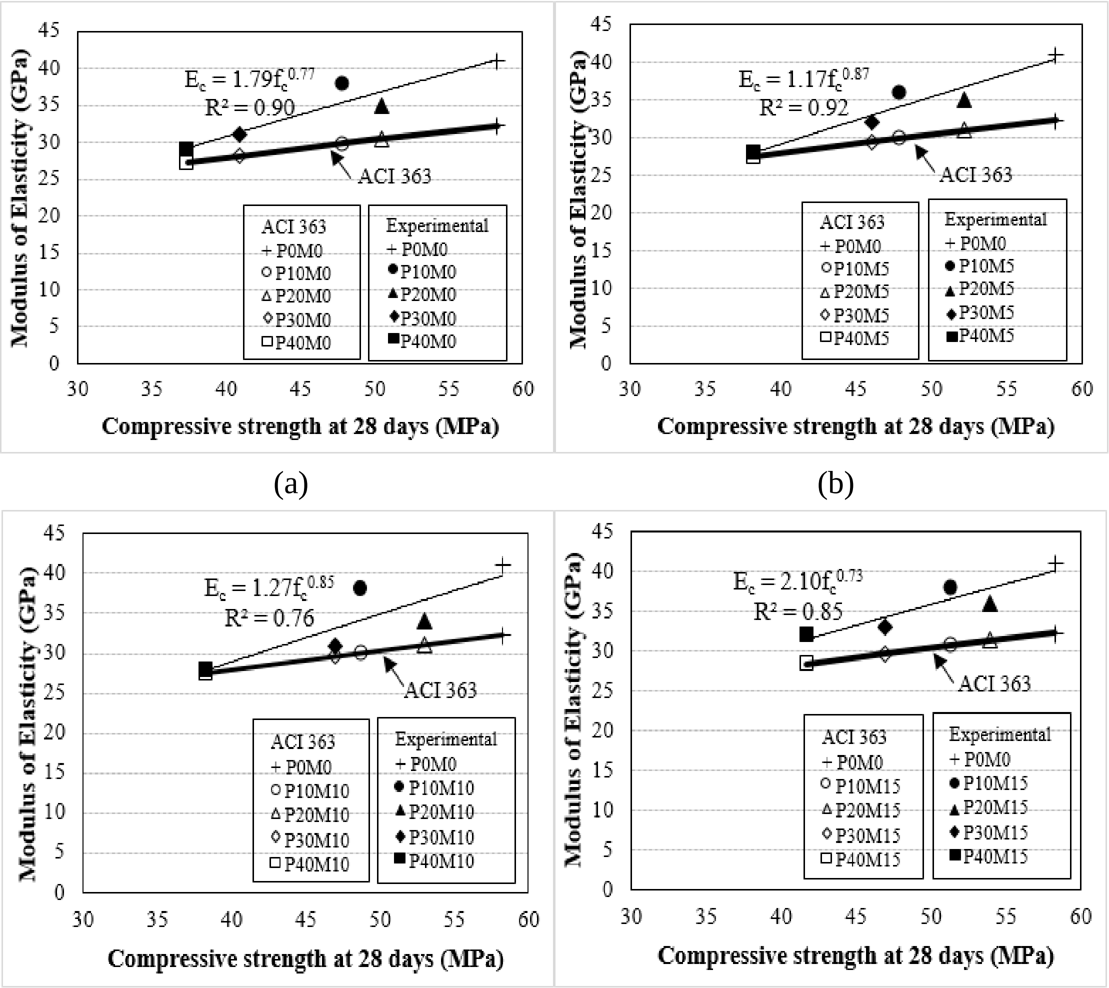
Figure 18a-d shows the relationship between compressive strength and elastic modulus of the concrete at 28 days and at different proportions of e-plastic replacement and different MD addition proportions.

The relationship between compressive strength, f_c and elastic modulus, E_c of HSC was calculated according to the building code of American Concrete Institute ACI 363 (ACI J 81, 1984), as given in the following expression:

$$E_c = 3.32(f_c)^{1/2} + 6.9 \tag{3}$$

in which f_c and E_c are expressed in MPa and in GPa, respectively.

Figure 17 shows that the relationship between the compressive strength and elastic modulus is in close agreement with the relationship suggested in ACI 363 at 0%, 5% and 15% MD additions, respectively. However, the correlation between the compressive strength and concrete's elastic modulus at different e-plastic replacement levels and MD additions decreased slightly with increased MD additions, i.e., R^2 values, being in the range of 0.90 to 0.92 in the equations proposed for 0% and 5% MD-bearing mixtures, reduced to 0.76 and 0.85 in the equations proposed for 10% and 15% MD-bearing mixtures. Moreover, the difference between the predicted and measured elastic moduli values increased by increasing strength of the concrete. Compared to the natural aggregates, e-plastic particles have lower modulus of elasticity. Therefore, the difference between modulus of elasticity of e-plastics and cement matrix becomes higher when natural aggregates are replaced with e-plastic particles. ITZ becomes weaker and stress transfer decreases so that the strength is affected negatively. According to the results, the effect of replacement of natural aggregates with e-plastic particles was more significant on compressive strength of concrete than the modulus of elasticity. Modulus of elasticity and compressive strength of concrete were not affected equally therefore, R^2 value decreases.



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

Figure 18: Relationship between compressive strength and modulus of elasticity elastic modulus at different e-plastic aggregate and MD addition (a) at 0% MD addition, (b) at 5% MD addition, (c) at 10% MD addition, (d) at 15% MD addition

5.2 Part 2 Experiments

Part 1 experiments were conducted on the concrete mixtures incorporating five different proportions of e-plastics (0%, 10%, 20%, 30% and 40%) and four different proportions of MD finer than 300 µm (0%, 5%, 10% and 15%). In part 2, MD finer than 180 µm was used at the proportions of 0% and 15% by weight of cement. The aim of utilizing MD finer than 180 µm was to investigate the effects of higher fineness on properties of concrete.

In addition, flexural strength, load-deflection relation under flexure, and the effects of high temperatures on unit weight, compressive strength and surface condition of concrete were investigated.

5.2.1 Workability

Figure 19 shows the slump values of concrete mixtures at different e-plastic replacement levels and MD additions. Concrete mixtures were designed with a constant w/c, and slump of concrete mixtures were kept in the range of 200±20 mm. Up to certain e-plastic replacement levels, superplasticizer amount decreased due to the smooth surface texture and almost zero water absorption capacity of e-plastics in order to achieve slump within the required range. At each e-plastic replacement level, slump of concrete without MD addition was around 210 and 220 mm. However, addition of 15% MD which was finer than 180 µm reduced the slump of concrete up to 180 mm.

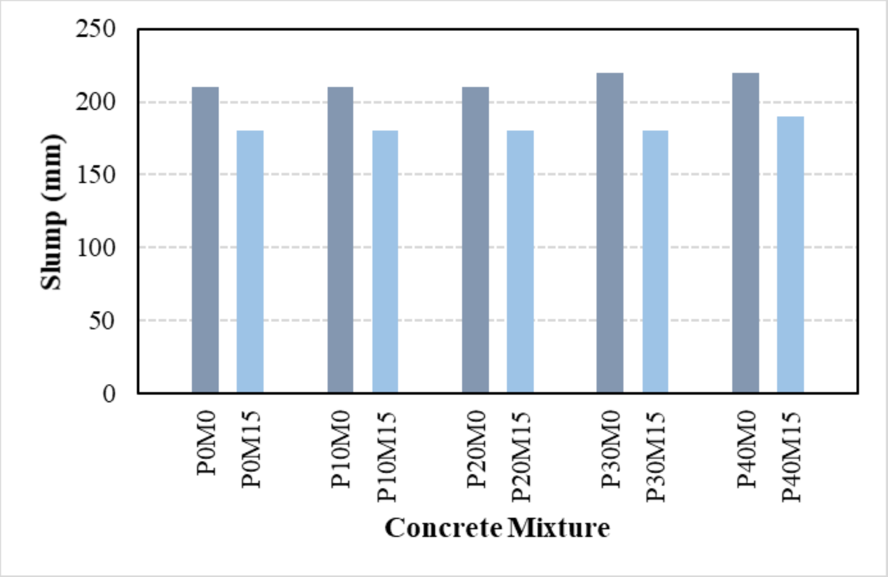


Figure 19: Slump values of concrete mixtures

5.2.2 Flexural Strength

Flexural strength is the ability of material to resist deformation under flexural load (Saikia et al., 2012). Figure 20 and Table 10 show the effect of e-plastic aggregate inclusion and MD addition on flexural strength of concrete. Concretes' flexural strength decreased with the substitution of natural aggregates with e-plastics compared to the control concrete without e-plastic and MD. The reduction was 19%, 16%, 20% and 21% at 10%, 20%, 30% and 40% replacement levels, respectively. The least reduction was found to be at 20% e-plastic replacement level. Even in the study of Yang et al. (2015), flexural strength of concrete increased up to 15% replacement level of sand with PP particles. However, in some studies flexural strength directly decreased with the inclusion of waste plastics as an aggregate in concrete/mortar. The reduction in flexural strength of mortar or concrete increased with the incorporation of fine PC (i.e., 32.8%) (Hannawi et al., 2010), fine PET (i.e., 32.8%) (Marzouk et al., 2007), and coarse HIPS (i.e., 36.99%, 37.38%, and 41.58% for w/c ratios of 0.45, 0.49 and 0.53) at 50% replacement level. On the other hand, the reductions at 30% and 40% replacement levels were found to be lower than the strength reduction reported by the Ozbakkaloglu et al. (2017) in which 30% coarse PP resulted in the 29.6% and 30.4% reductions in NSC and HSC mixes, respectively. The reduction in flexural strength could be attributed to that the strength of plastics is lower than that of natural aggregates (Batayneh et al., 2007), and the weak bond between e-plastic and cement paste due to smooth surfaces and hydrophobic nature of plastics (Ismail et al., 2018; Ozbakkaloglu et al., 2010). Notwithstanding the decreases in flexural strength at all inclusion levels, concrete beams with e-plastic aggregates did not split into two after failure as shown in Figure 21. Moreover, 15% MD addition at 0% e-plastic replacement level improved the flexural strength by 10%. In addition to this, the flexural strength increased by 3.6%, 3.8%, 4.1% and 3.5% at 10%, 20%, 30% and 40% replacement levels with the 15% addition of MD. This could be attributed to the filler effect of MD.

Therefore, when compared to the control concrete (P0M0), minimum reduction of 13% and maximum reduction of 21% occurred in P20M15 and P40M0, respectively.

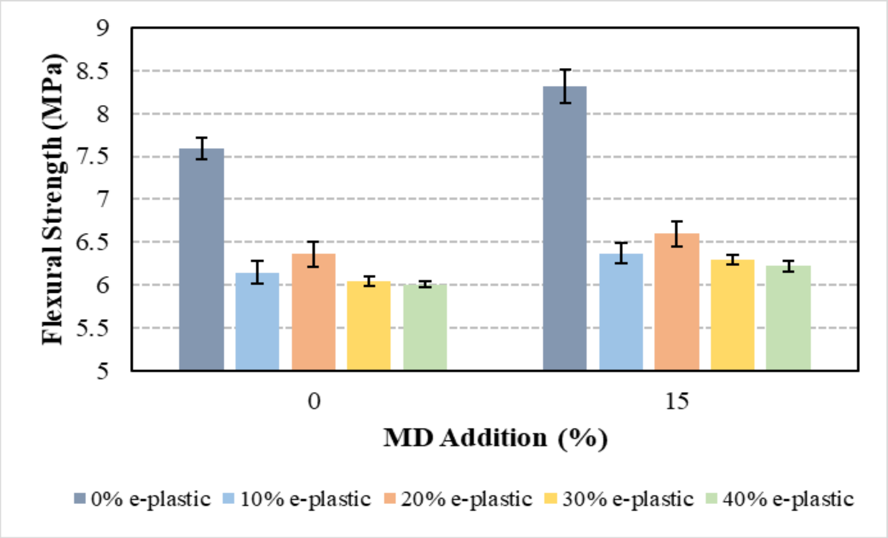


Figure 20: Effect of e-plastic aggregate inclusion and MD addition on the 28 day-flexural strength of HSC

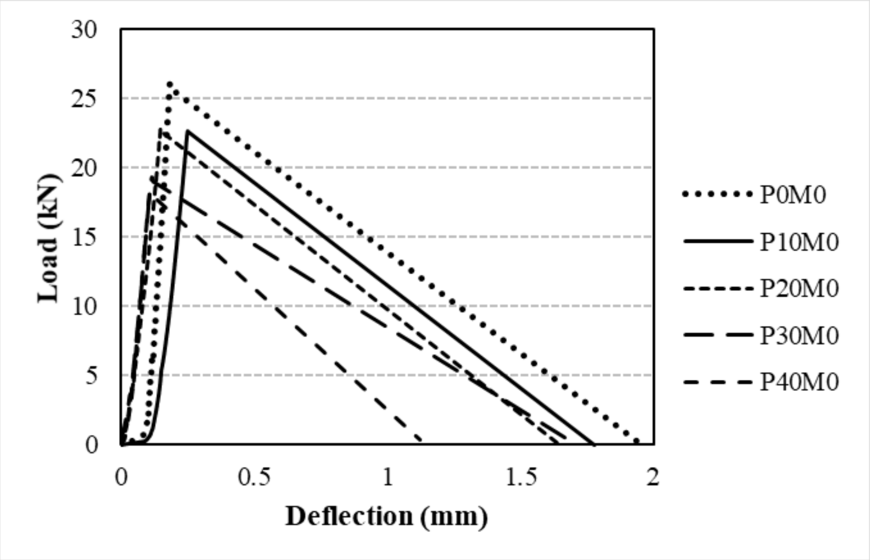
Table 10: Flexural strength of concrete specimens

Mixture	Flexural Strength (MPa)			
	1	2	3	Average
P0M0	7.48	7.57	7.72	7.59
P0M15	8.52	8.13	8.28	8.31
P10M0	6.30	6.12	6.04	6.15
P10M15	6.26	6.37	6.49	6.37
P20M0	6.53	6.26	6.29	6.36
P20M15	6.48	6.76	6.55	6.60
P30M0	6.05	6.11	6.00	6.05
P30M15	6.24	6.34	6.32	6.30
P40M0	6.04	6.02	5.98	6.01
P40M15	6.17	6.29	6.19	6.22

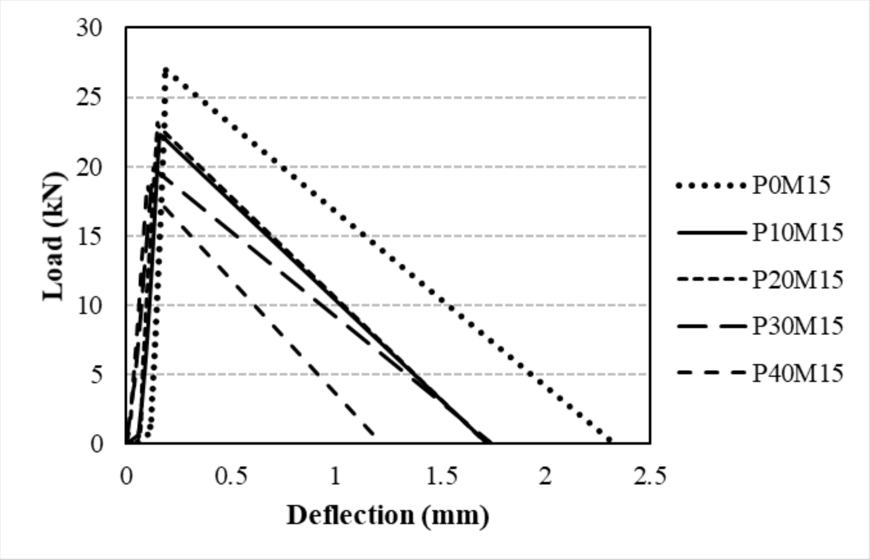
Figure 21: Concrete beam with inclusion of e-plastic aggregates in flexural strength test

5.2.3 Flexural Toughness

28-day flexural load-deflection curves of the concrete beams with and without e-plastics are illustrated in Figure 22-a and Figure 22-b at 0% MD and 15% MD additions, respectively. From the figures, it could be seen that the ultimate strength of concrete beams at all e-plastic inclusion levels were lower than that of control concrete without e-plastic aggregates. The lowest and highest decrease in ultimate strength occurred in 20% and 40% e-plastic replacement levels, respectively. Although the ultimate strength of concrete specimens decreased with an increase in replacement level, deflection at 10%, 20% and 30% replacement level did not vary significantly at failure and almost similar deflection values were observed with or without MD addition, except at 40% replacement level. Especially, in Figure 22-a, it can be seen that deflection at 30% e-plastic replacement level was found to be higher than the deflection occurred at 20% e-plastic replacement level. Additionally, as shown in Figure 22-b, although the ultimate strength at 30% e-plastic replacement level was lower than the those were obtained at 10% and 20% replacement levels, deflection at 30% e-plastic replacement level was almost same with the deflections occurred at 10% and 20% e-plastic replacement levels.



(a)



(b)

Figure 22: Effect of e-plastic aggregate inclusion and MD addition (a) at 0%, (b) at 15% on load- deflection curve of concrete

Figure 23 presents the flexural toughness values obtained from the area under the load- deflections curve. As it can be seen from the figure, flexural toughness reduced with the inclusion of e-plastic aggregates. However, slight increase in flexural toughness value was observed with the addition of 15% MD. The effect of MD addition was more pronounced at 0% e-plastic replacement level which was 15%. The highest and lowest reductions of 24.1% and 59.5% were observed in P20M15 and P40M0, respectively. The reduction in toughness could be attributed to the lower ultimate strength and deflection of beams with e-plastic aggregates than control concrete since the area under the load-deflection curves decreased with a decrease in ultimate strength and deflection.

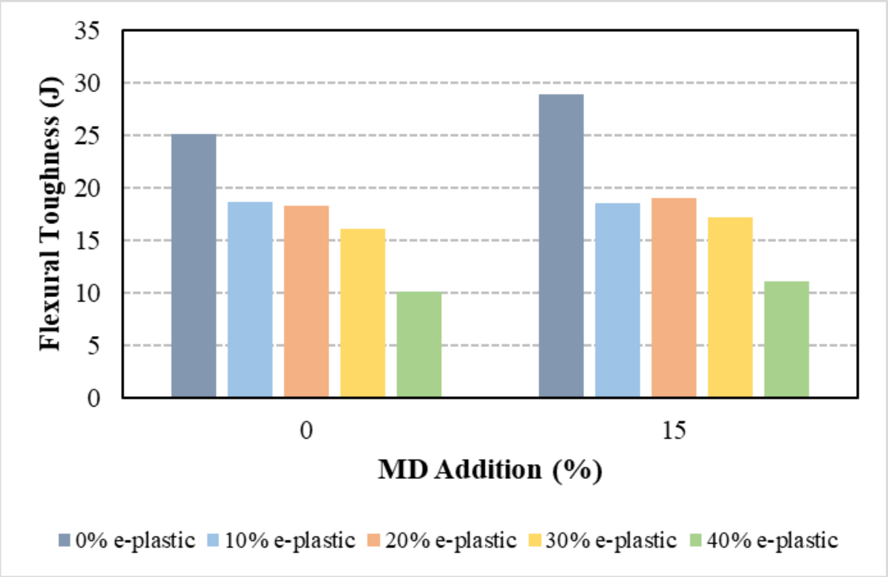


Figure 23: Effect of e-plastic aggregate inclusion and MD addition on flexural toughness of HSC

5.2.4 Unit Weight Loss under High Temperatures

Dry unit weight of concrete mixtures showed reduction with an increase in e-plastic replacement level at room temperature due to lower density of e-plastic particles as shown in Figure 24 and Table 11. The reductions in dry unit weight at an ambient temperature were 2.5%, 4.4%, 6.7% and 7.7% at 10%, 20%, 30% and 40% e-plastic replacement levels compared to the control concrete (P0M0). However, 15% MD addition improved the dry unit weight between 1.6% and 3.2%.

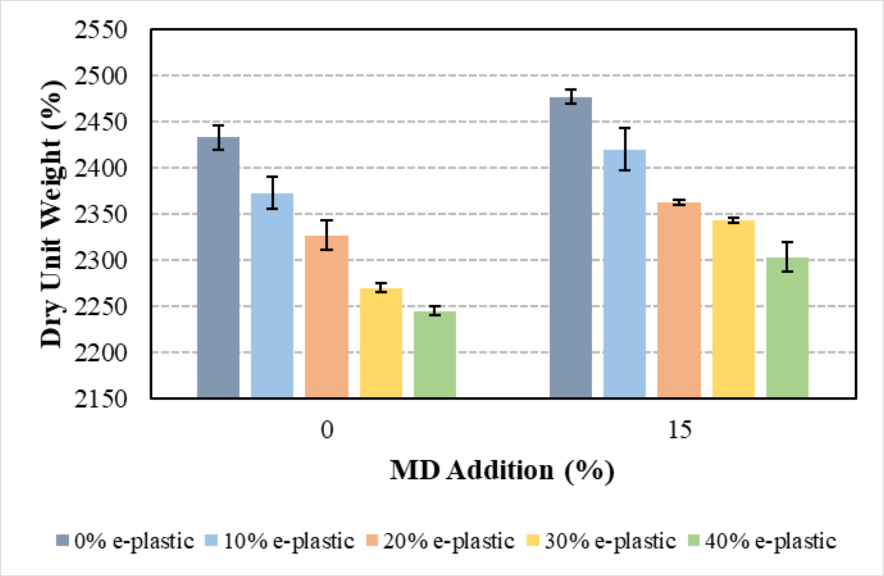


Figure 24: Dry unit weight of concrete mixtures at an ambient temperature

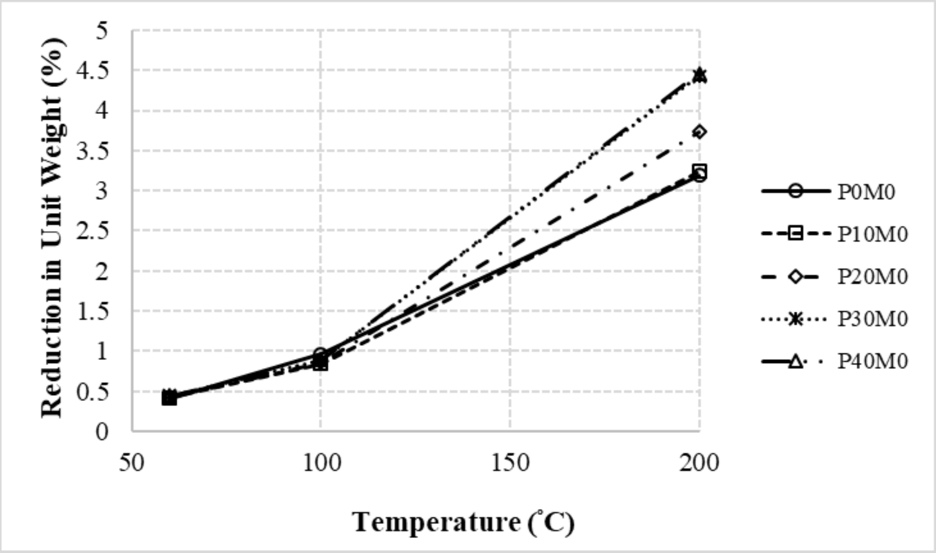
Table 11: Dry unit weight of concrete specimens

	Mass (kg)				Unit Weight (kg/m^3)
Mixture	**1**	**2**	**3**	**Average**	**Average**
P0M0	2.445	2.435	2.420	2.433	2433
P0M15	2.470	2.485	2.475	2.477	2477
P10M0	2.390	2.375	2.355	2.373	2373
P10M15	2.445	2.400	2.415	2.420	2420
P20M0	2.345	2.320	2.315	2.327	2327
P20M15	2.365	2.365	2.360	2.363	2363
P30M0	2.270	2.275	2.265	2.270	2270
P30M15	2.340	2.345	2.345	2.343	2343
P40M0	2.245	2.250	2.240	2.245	2245
P40M15	2.285	2.310	2.315	2.303	2303

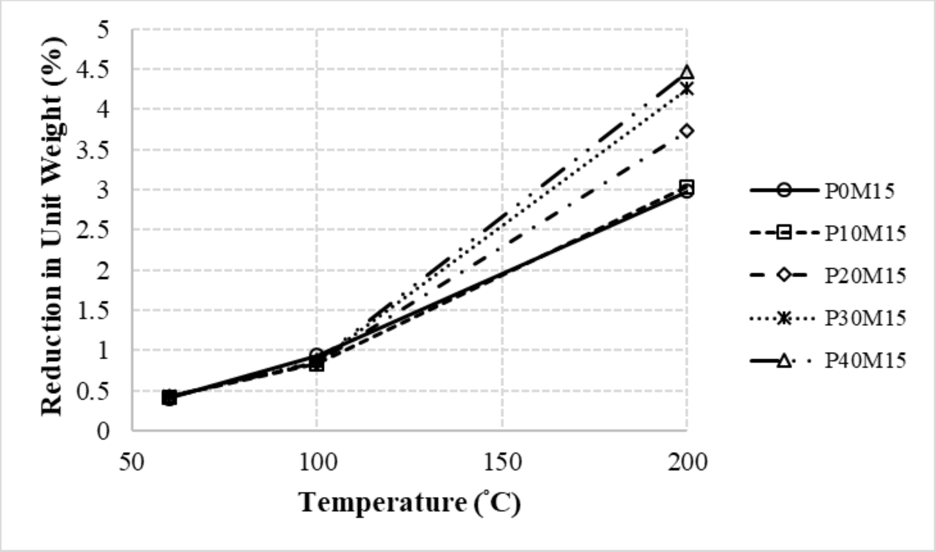
In addition, unit weight of the cube specimens was determined before and after they were exposed to high temperatures of 60ºC, 100ºC and 200ºC for 2 hours. Unit weight loss values of concrete mixtures at 0%, 10%, 20%, 30% and 40% e-plastic replacement levels and at 0% and 15% MD additions are given in Figure 25-a and

Figure 25-b, respectively. Additionally, unit weights of unheated and heated concrete specimens are provided in Appendix C.

As it can be seen from the figures, the reduction in unit weight became higher with an increase in the temperature. This could be attributed to the released water from the cement paste and the formation of the air voids as it is also stated by Bingöl et al. (2018). At the temperatures of 60ºC and 100ºC, the effect of e-plastic replacement and MD addition on unit weight loss was insignificant. However, the reduction in unit weight became higher with an increase in e-plastic replacement level at 200ºC and reached to 4.47% at 40% e-plastic replacement level. Additionally, the effect of MD addition was more pronounced at 200ºC by decreasing the unit weight loss. Moreover, P30M0 and P40M0 specimens were performed almost the same behavior when exposed to high temperatures as shown in Figure 25-a.



(a)



(b)

Figure 25: Effect of high temperatures, e-plastic aggregate and MD addition (a) at 0%, (b) at 15% on unit weight loss of HSC

5.2.5 Compressive Strength Loss Under High Temperatures

Composite structure of concrete and physical and chemical composition of the cement paste affect the behavior of concrete under exposure to high temperatures (Davie et al., 2006). Compressive strength of concrete under high temperatures is affected by the moisture content. Changes in moisture content and porosity due to loss of capillary water, physically bonded water and chemically bonded water cause variations in the strength of concrete. Capillary water behaves like free bulk water and when concrete is heated, firstly capillary water evaporates. Physically bonded water is adsorbed water that it is physically bound to the solid and it evaporates when concrete is further heated. In addition, chemically bonded water which is usually used in hydration process is not decomposed below 105°C. However, it releases into the pores at higher temperatures (Shen et al., 2019). Strength changes under high temperatures can also be attributed to the deterioration of aggregates, decomposition of hydrated pastes and thermal incompatibilities between cement paste and aggregate that lead to stress concentrations and micro-cracking (Mindess et al., 2003). Additionally, when concrete is heated rapidly, a high temperature difference between the deeper zone and the surface of a specimen occurs and therefore explosive spalling may occur during heating (Peng et al., 2006).

Figure 26-a and Figure 26-b and Table 12 shows the compressive strength values of concrete mixtures at an ambient and at the temperatures of 60ºC, 100ºC and 200ºC at all 0%, 10%, 20%, 30% and 40% e-plastic replacement levels and at 0% and 15% MD addition, respectively.

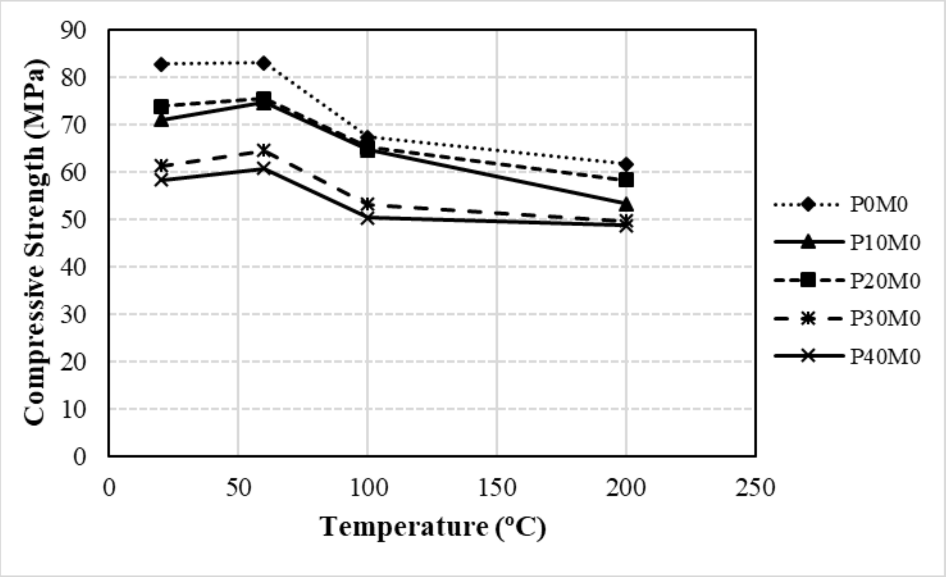
Figure 26 shows that, at an ambient temperature, concretes' compressive strength with and without MD were lower than the control concrete at all e-plastic inclusion levels. The reduction in concrete's compressive strength without MD were 14%, 11%, 26% and 30% at 10%, 20%, 30% and 40% e-plastic replacement levels, respectively compared to that of control concrete (P0M0). The reason of the least reduction in 20% replacement may be attributed to that some voids in concrete may be filled with fine plastic particles at lower replacement levels as it was also stated by Yang et al. (2015). However, since the compressive strength of concrete at all e-plastic replacement levels was found to be lower than the control concrete, this may be attributed to the very low bond strength between the surface of e-plastic and cement paste and hydrophobic nature of e-plastic that prevents cement hydration reaction by restricting water movement (Saikia et al., 2012). Lower modulus of elasticity of e-plastic particles than natural aggregates also reduces the compressive strength of concrete (Ozbakkaloglu et al., 2010). Additionally, lower adhesion characteristics between mortar and aggregate creates voids in concrete that affects strength negatively (Saxena et al., 2018). High volumes of free water may be accumulated around plastic particles at higher replacement levels due to almost zero water absorption and may affect strength negatively (Frigione, 2010; Saikia et al., 2014; Yang et al., 2015). However, as it can be seen from the Figure 26-b, 15% MD addition improved the concretes' compressive strength slightly since it acts as filler material. MD particles may act as a micro-filler at the interfaces between cement paste and aggregate and or in the pores as also stated by Keleştemur et al. (2014).

At all e-plastic replacement levels and at 0% and 15% MD additions, a slight increase in compressive strength was observed in all concrete mixtures when they were exposed to the temperature of 60ºC for 2 hours compared to the concrete at a room temperature. The increase in compressive strength could be related with the moisture in the concrete. At room temperature, the pores in the concrete may be fully or partially filled with fluids; liquid water, water vapor, and dry air (Davie et al., 2006). Therefore, there is a relationship between the porosity and compressive strength of concrete at room temperature (Vodák et al., 2004). When concrete is tested in saturated state, water in the pores causes pore pressure and results in reduction in strength. Therefore, at 60ºC the strength of the dried concrete was higher than the concrete at room temperature. Similar conclusions were also drawn by other researchers. When compressive strength of fully saturated and completely dried concrete was tested, strength of dry concrete was found to be higher than that of saturated concrete (Wang et al., 2007; Wang et al., 2009). Additionally, Yurtdas et al. (2006), suggested that the dry concrete has greater strength than saturated concrete. Up to 20% increase also occurs in compressive strength of dry concrete compared to the saturated concrete due to the reduction in disjoining pressure (Mindess et al., 2003).

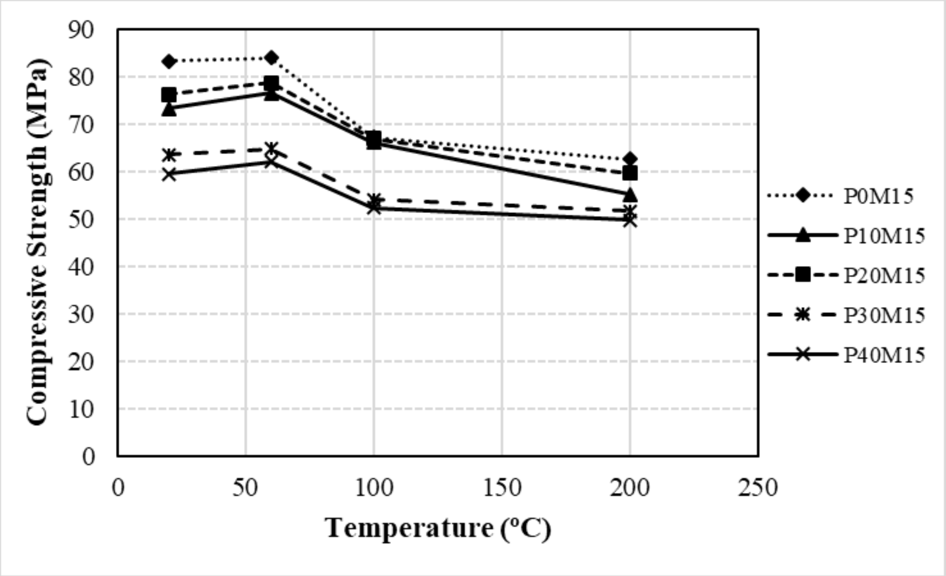
However, beyond 60ºC, compressive strength values decreased with an increase in temperature. Compressive strength values at all e-plastic replacement levels with and without MD were lower than the values observed at the ambient temperature.

Although there was a slight increase up to 5% in compressive strength values at 60ºC compared to the unheated specimens, concretes' compressive strength decreased with an increase in e-plastic replacement level compared to the control concrete (P0M0) at 60ºC. However, among all e-plastic replacement levels at 0% MD addition, the lowest reduction of 9.2% was observed in P20M0 mix compared to the

P0M0 at 60ºC. Moreover, it could be seen from Figure 26-b that, when 15% MD was used as an additive, the reduction in concrete's compressive strength became lower than that of without MD. For example, the lowest decreases of 6.2% and 5.2% were observed in P20M15 mixture compared to the P0M15 and P0M0 respectively at 60ºC.



(a)



(b)

Figure 26: Effect of high temperatures, e-plastic aggregate inclusion and MD addition (a) at 0%, (b) at 15% on compressive strength of HSC

Table 12: Compressive strength of concrete specimens at an ambient and at 60°C, 100°C, 200°C

Mixture		**Temperature**			
		20°C	**60°C**	**100°C**	**200°C**
		Compressive Strength (MPa)			
P0M0	1	83.3	84.1	67.2	60.9
	2	82.5	81.6	68.0	60.8
	3	82.3	83.2	66.4	63.2
	Average	**82.7**	**83.0**	**67.2**	**61.6**
P0M15	1	82.0	83.7	66.3	60.5
	2	83.1	84.3	67.2	63.6
	3	84.6	83.6	68.1	63.8
	Average	**83.2**	**83.9**	**67.2**	**62.6**
P10M0	1	71.6	70.2	60.1	53.1
	2	70.7	76.6	64.4	53.2
	3	70.1	76.8	69.3	53.2
	Average	**70.8**	**74.5**	**64.6**	**53.2**
P10M15	1	73.3	74.8	65.3	55.6
	2	73.9	78.1	66.1	54.5
	3	72.7	76.6	66.9	55.4
	Average	**73.3**	**76.5**	**66.1**	**55.2**
P20M0	1	74.2	74.7	64.1	58.1
	2	73.0	74.8	65.2	57.1
	3	73.9	76.6	65.9	59.3
	Average	**73.7**	**75.4**	**65.1**	**58.2**
P20M15	1	75.9	78.6	66.7	59.8
	2	76.1	78.5	67.9	60.0
	3	76.8	78.9	66.1	59.0
	Average	**76.3**	**78.7**	**66.9**	**59.6**
P30M0	1	62.0	64.2	51.3	49.9
	2	60.7	64.8	53.7	49.1
	3	60.9	64.3	54.1	49.8
	Average	**61.2**	**64.4**	**53.0**	**49.6**
P30M15	1	62.7	64.9	52.6	52.4
	2	65.9	64.9	56.5	50.8
	3	61.8	64.4	53.2	51.9
	Average	**63.5**	**64.7**	**54.1**	**51.7**
P40M0	1	57.8	60.7	51.0	48.1
	2	59.0	60.4	49.6	49.1
	3	58.0	60.9	50.3	48.6
	Average	**58.3**	**60.7**	**50.3**	**48.6**
P40M15	1	58.3	61.1	52.3	50.3
	2	58.5	62.8	53.8	48.0
	3	61.7	62.2	51.0	51.1
	Average	**59.5**	**62.0**	**52.4**	**49.8**

As it was stated in the above paragraphs, beyond 60ºC, compressive strength decreased at the temperatures of 100ºC and 200ºC compared to that of the unheated specimens and the reduction in compressive strength values became higher at 200ºC. Over 100°C, a significant amount of water vapor is generated inside the concrete. High inner pressure caused by water vapor leads to formation of a large number of cracks inside the concrete (Phan et al., 2001). Dehydration of chemically bonded water may increase the connectivity of pores and micro-cracks as a result of the loss of the chemically bonded water and strength is affected negatively as it was also observed by Shen et al. (2019). For example, among all specimens at all e-plastic replacement levels with and without MD additions, the decrease in compressive strength with an increase in temperature reached to 19% and 26% at the temperature of 100ºC and 200ºC, respectively compared to that of the unheated specimens. According to the Noumowe (2005), 170°C is the temperature where the first stage of the dehydration of crystal structure of C-S-H occurs and results in more porous concrete matrix compared to that at room temperature. In the study of Shen et al., (2019), the strength loss reached to the 30.66% when concrete samples were heated up to 250 ºC. According to Keleştemur et al. (2014), MD improves the resistance of concrete since it reduces the voids and modifies the interface between cement paste and aggregate.

In addition, as it was observed in the 60ºC, the reduction in compressive strength became more pronounced at all exposure temperatures with a higher e-plastic replacement level compared to that of the control concrete (P0M0) as it was also reported by the other researchers (Ozbakkaloglu et al.,2017; Senthil Kumar et al., 2018).

As a result, at 0% MD addition, compressive strength of concrete decreased by 22%, 21%, 36% and 39% and 36%, 30%, 40% and 41% when concrete specimens were exposed to the temperatures of 100°C and 200°C at the e-plastic replacement levels of 10%, 20%, 30% and 40%, respectively compared to the control concrete (P0M0) at an ambient temperature. However, when the temperature reached to 100°C and 200°C, the reduction in compressive strength at all e-plastic replacement levels were found to be slightly lower in the mixtures containing MD. The reductions in compressive strength at 10%, 20%, 30% and 40% e-plastic replacement levels and 15% MD additions were 20%, 19%, 35% and 37% and 33%, 28%, 37% and 40%, respectively at the temperatures of 100°C and 200°C compared to that of the control concrete (P0M0) at room temperature.

5.2.6 Surface Condition of Concrete Specimens

The concrete specimens at 0%, 10%, 20%, 30% and 40% e-plastic replacement levels and 0% and 15% MD additions were subjected to the temperatures of 60°C, 100°C, 200°C and 300°C for 2 hours. After removal from the furnace, the effect of temperatures on their surface was detected by visual observation.

Up to 200ºC, no color change was observed on the concrete surfaces. However, at 300ºC, color changes observed on the concrete surfaces as shown in Figure 30. In addition, e-plastic particles close to the concrete surface started to melt at 200ºC as shown in Figure 28, whereas e-plastic particles inside the concrete was not affected as shown in Figure 29. Moreover, burned e-plastic particles were visible on the concrete surfaces at 300ºC yet the e-plastic particles inside the concrete were not affected. Therefore, the effect is more pronounced for the e-plastic particles located on the surface of concrete specimens than in the inner parts of the concrete since concrete is a good isolator which results in the temperature gradient in the specimen as it was also stated by the Albano et al. (2009). Additionally, Figure 31 shows the damaged e-plastic particles obtained from the concrete surface after exposing to 300ºC.

According to DSC analysis of e-plastic particles as can be seen in Figure 6, the glass transition zone temperature of e-plastic is 94.96ºC. Additionally, TGA analysis of e-plastics which is given in Figure 5 showed that, weight loss of e-plastics firstly initiated around 160ºC and 170ºC and it became more pronounced at 300ºC compared to the 200ºC. Beyond 300ºC, the weight loss of e-plastic particles increased dramatically. The reason of burnt e-plastic particles on the concrete surfaces at 300°C could be related with the weight loss of particles that became more pronounced at 300°C than 200°C as shown in Figure 5.

Figure 27: Surface of the concrete specimen after exposed to 100ºC

Figure 28: Surfaces of concrete specimens after exposure to 200ºC

Figure 29: Splitted surface of concrete specimen after exposure to 200ºC

Figure 30: Surfaces of concrete specimens after exposure to 300ºC

Figure 31: Damaged e-plastic particles after exposure to 300ºC

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

This study mainly focuses on the use of both e-plastic and MD in order to evaluate their effects on the mechanical properties and behavior of the hardened concrete. In part 1 experiments, MD finer than 300 μm was used at the proportions of 0%, 5%, 10% and 15% by weight of cement. However, in order to investigate the effect of finer particles on properties of concrete, MD finer than 180 μm was used at the proportions of 0% and 15% in part 2 experiments. Compressive, splitting tensile and flexural strength values, modulus of elasticity, stress-strain relationship under compression, load-deflection relation under flexure, toughness, permeability and the effects of high temperatures on unit weight, compressive strength and surface condition of concrete were investigated and the following conclusions have been drawn:

- Incorporation of e-plastic in concrete reduced the dry unit weight of the concrete. The highest reduction was found to be in concrete mixes with a 40% e-plastic replacement level. When MD finer than 300 μm was used at the proportions of 15%, dry unit weight increased between 1.6% and 3.5%. Additionally, MD finer than 180 μm improved dry unit weight between 1.6% to 3.2%, respectively in concrete mixes with e-plastic aggregates.
- Regardless of the e-plastic aggregate substitution level, the 28-day compressive strength, splitting tensile strength and moduli of elasticity of the

test mixtures were lower than that of the control concrete. The decrease in splitting tensile strength occurred at lower level than the compressive strength. The lowest and highest reductions in compressive strength were observed at 20% and 40% e-plastic aggregate replacement levels, respectively. However, the addition of the MD partially compensated the negative effect of the presence of the e-plastic aggregate in the concrete. The fact was more pronounced at 15% MD addition. At the 15% MD additions, MD finer than 300 µm improved compressive strength up to 15% but in part 2 experiments MD finer than 180 µm improved the strength up to 4%. Splitting tensile strength of the 10% e-plastic mixture containing 15% MD was very close to that of the control concrete however, MD addition had no significant effect on the elastic modulus of e-plastic aggregate mixtures.

- The compressive stress-strain curves revealed that the test mixtures had lower ultimate strength, and toughness yet higher ductility compared to the control concrete. Except for the mixtures with 40% e-plastic replacement levels, the stresses corresponding to 0.004 strain in the test mixtures were higher than that of the control concrete, denoting the steeper character of the ascending part of stress-strain diagram of the latter mixture.
- Regardless of MD content, replacement of 10% of aggregate with e-plastic aggregate resulted in a lower water penetration depth than that of the control mixture. However, the permeability increased further by either increasing the e-plastic aggregate content or decreasing the MD content of these mixtures.
- The correlation between the compressive strength and concrete’s elastic modulus at different e-plastic substitution levels and MD additions decreased slightly with increased e-plastic and MD additions, i.e., R^2 values, being in

the range of 0.90 to 0.92 in the equations proposed for 0 and 5% MD-bearing mixtures, reduced to 0.76 and 0.85 in the equations proposed for 10 and 15% MD-bearing mixtures.

- With the inclusion of e-plastic aggregates, flexural strength at all e-plastic replacement levels were found to be lower than the P0M0 (control concrete). Reductions ranged from 16% to 21% in concrete mixtures without MD additions. 15% MD addition improved flexural strength around 4% in concrete mixtures with e-plastic aggregates. Minimum reduction of 13% and maximum reduction of 21% were occurred in P20M15 and P40M0, respectively compared to the P0M0 in concrete with e-plastic aggregates.
- From the load-deflection curves under flexure, it could be seen that the lowest and highest decrease in ultimate strength occurred in 20% and 40% e-plastic replacement levels, respectively. Although ultimate strength at 30% e-plastic replacement level was lower than 10% and 20% e-plastic replacement levels, deflections at 30% e-plastic replacement level were found to be close to the deflections occurred at 10% and 20% e-plastic replacement levels.
- Under high temperatures, the reduction in unit weight increased with an increase in temperature. At the temperatures of 60ºC and 100ºC, the effect of e-plastic replacement and MD addition on unit weight loss were insignificant. However, the reduction became higher with an increase in e-plastic replacement level at 200ºC and reached to 4.47% at 40% e-plastic replacement level. Additionally, the effect of MD addition was more pronounced at 200ºC by decreasing the unit weight loss.
- At the ambient temperature, concrete’s compressive strength, with and without MD, were lower than the control concrete at all e-plastic replacement

levels. Reduction in compressive strength at all exposed temperatures became more pronounced with an increase in e-plastic replacement level compared to the control concrete (P0M0). However, slight increases in compressive strength values were observed at 60ºC. Beyond 60ºC, the reduction in compressive strength with an increase in temperature reached to 19% and 26% at the temperature of 100ºC and 200ºC, respectively compared to the unheated specimens. However, addition of MD improved the resistance of concrete specimens since it may modify the ITZ between cement paste and aggregates.

- When concrete surfaces were analysed with visual observation, color changes were observed on the concrete surface at 300ºC. Up to 200ºC, there were no variations on the surface condition of concrete but melted e-plastic particles were observed on the concrete surfaces at 200ºC. Moreover, burnt e-plastic particles were also observed on the concrete surfaces at 300ºC.

6.2 Recommendations for Future Studies

- The surfaces of melted e-plastics can be coated with MD and the effects of coated e-plastics on the properties of concrete can be investigated.
- The approach of utilization of waste materials in concrete production can be further developed since it can be a beneficial way of using waste materials and therefore providing more environmentally friendly concrete.
- Effects of MD additions on the mechanical behaviour and performance of concrete can be investigated at percentages higher than 15%.

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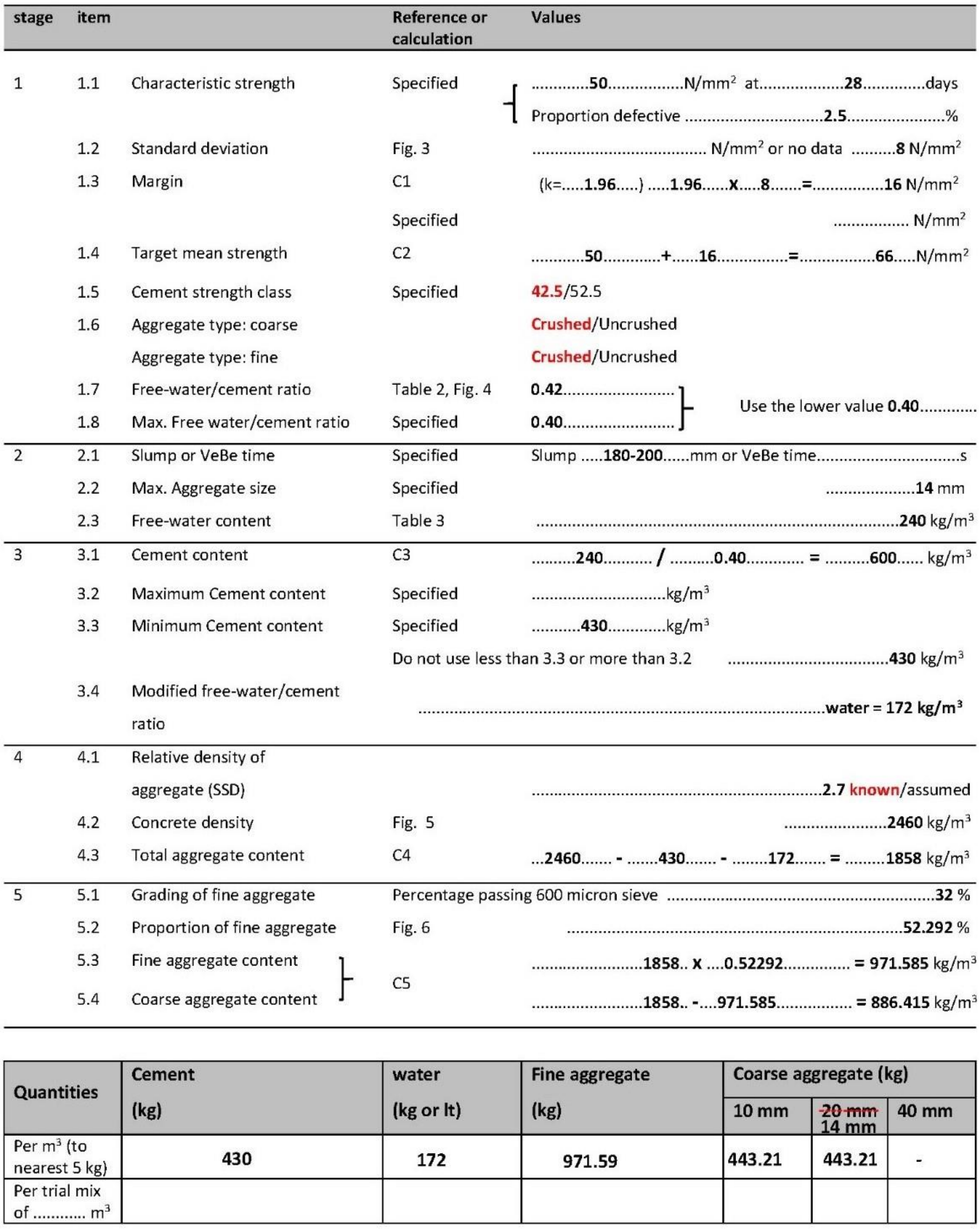
APPENDICES

Appendix A: Mix Design Values for P0M0

Table 13: Concrete mix design form (BRE Method)



stage	item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	............**50**................N/mm^2 at...................**28**..............days Proportion defective ....**2.5**......................%
	1.2	Standard deviation	Fig. 3	.... N/mm^2 or no data ....**8** N/mm^2
	1.3	Margin	C1	(k=.....**1.96**.....) .....**1.96**......**X**.....**8**.......**=**................**16** N/mm^2
			Specified	.... N/mm^2
	1.4	Target mean strength	C2	............**50**.............**+**......**16**................**=**.................**66**.....N/mm^2
	1.5	Cement strength class	Specified	**42.5**/52.5
	1.6	Aggregate type: coarse		**Crushed**/Uncrushed
		Aggregate type: fine		**Crushed**/Uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig. 4	**0.42**......................... Use the lower value **0.40**............
	1.8	Max. Free water/cement ratio	Specified	**0.40**.........................
2	2.1	Slump or VeBe time	Specified	Slump .....**180-200**......mm or VeBe time...............................s
	2.2	Max. Aggregate size	Specified	....................**14** mm
	2.3	Free-water content	Table 3	....**240** kg/m^3
3	3.1	Cement content	C3	..........**240**........... **/** ....**0.40**............. **=** ....**600**...... kg/m^3
	3.2	Maximum Cement content	Specified	..............................kg/m^3
	3.3	Minimum Cement content	Specified	...........**430**.............kg/m^3
			Do not use less than 3.3 or more than 3.2	....................................**430** kg/m^3
	3.4	Modified free-water/cement ratio		....**water = 172 kg/m^3**
4	4.1	Relative density of aggregate (SSD)		....**2.7 known**/assumed
	4.2	Concrete density	Fig. 5	.......................**2460** kg/m^3
	4.3	Total aggregate content	C4	...**2460**....... **-** ....**430**....... **-** ....**172**....... **=** ....**1858** kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 micron sieve	....**32** %
	5.2	Proportion of fine aggregate	Fig. 6	....**52.292** %
	5.3	Fine aggregate content	C5	.........................**1858**.. **X** ....**0.52292**............... **= 971.585** kg/m^3
	5.4	Coarse aggregate content		.........................**1858**.. **-**....**971.585**................. **= 886.415** kg/m^3

Quantities	**Cement (kg)**	**water (kg or lt)**	**Fine aggregate (kg)**	**Coarse aggregate (kg)**		
				10 mm	**~~20 mm~~ 14 mm**	**40 mm**
Per m^3 (to nearest 5 kg)	**430**	**172**	**971.59**	**443.21**	**443.21**	**-**
Per trial mix of .... m^3						

Mass of natural aggregates for control mixture is given below in Table 14.

Table 14: Mass of natural aggregates for P0M0

Mass of fine aggregate (0-5 mm)	**Mass of coarse aggregate (5-10 mm)**	**Mass of coarse aggregate (10-14 mm)**
971.59 kg/m^3	443.21 kg/m^3	443.21 kg/m^3

At all e-plastic replacement levels,

- 10% of 0-5 mm fine aggregates were substituted with e-plastic particles having the sizes from 0 to 5 mm.
- 70% of 5-10 mm coarse aggregates were substituted with e-plastic particles having the sizes from 5 to 10 mm.
- 20% of 10-14 mm coarse aggregates were substituted with e-plastic particles having the sizes from 10 to 14 mm.

Volume of natural aggregates was calculated from the formula given below:

$$\rho_{aggregate} = \frac{M_{aggregate}}{V_{aggregate}}$$

Volume of fine aggregate (0-5mm):

$$2700 = \frac{971.59}{V_{(0-5)}}$$

$$V_{(0-5)} = 0.35985 \text{ m}^3$$

Volume of coarse aggregate (5-10mm):

$$2700 = \frac{443.21}{V_{(5-10)}}$$

$$V_{(5-10)} = 0.16415 \text{ m}^3$$

Volume of coarse aggregate (10-14mm):

$$2700 = \frac{443.21}{V_{(10-14)}}$$

$$V_{(10-14)} = 0.16415 \text{ m}^3$$

Table 15: Volume of natural aggregates

Volume of fine aggregate (0-5 mm)	**Volume of coarse aggregate (5-10 mm)**	**Volume of coarse aggregate (10-14 mm)**
0.35985 m^3	0.16415 m^3	0.16415 m^3

Calculations of volume and mass of e-plastic aggregates and natural aggregates at 10% replacement level are given as an example below:

Volume of e-plastic particles having the sizes between 0 and 5 mm:

$$V_{(0-5)} = 0.35985x0.10x0.10 = 3.5985\ x\ 10^{-3} m^3$$

Mass of e-plastic particles having the sizes between 0 and 5 mm:

$$\rho_{e-plastic} = \frac{M_{e-plastic}}{V_{aggregate}}$$

$$1070 = \frac{M_{e-plastic}}{3.5985\ x\ 10^{-3}}$$

$$M_{e-plastic} = 3.85\ kg$$

Volume of e-plastic particles having the sizes between 5 and 10 mm:

$$V_{(5-10)} = 0.16415x0.10x0.70 = 0.01149\ m^3$$

Mass of e-plastic particles having the sizes between 5 and 10 mm:

$$\rho_{e-plastic} = \frac{M_{e-plastic}}{V_{aggregate}}$$

$$1070 = \frac{M_{e-plastic}}{0.01149}$$

$$M_{e-plastic} = 12.29\ kg$$

Volume of e-plastic particles having the sizes between 10 and 14 mm:

$$V_{(10-14)} = 0.16415x0.10x0.20 = 3.283\ x\ 10^{-3}\ m^3$$

Mass of e-plastic particles having the sizes between 10 and 14 mm:

$$\rho_{e-plastic} = \frac{M_{e-plastic}}{V_{aggregate}}$$

$$1070 = \frac{M_{e-plastic}}{3.283\ x\ 10^{-3}}$$

$$M_{e-plastic} = 3.51\ kg$$

Volume of natural aggregates at 10% e-plastic replacement level:

Volume of fine aggregate (0-5mm):

$$V_{(0\text{-}5mm)} = 0.35985 - (3.5985\ x\ 10^{-3}) = 0.35625\ m^3$$

Mass of fine aggregate (0-5mm):

$$m = \rho\ x\ V$$

$$m = 2700\ x\ 0.35625$$

$$m = 961.87\ kg$$

Volume of coarse aggregate (5-10mm):

$$V_{(5\text{-}10\text{mm})} = 0.16415 - 0.01149 \ = 0.15266 \, m^3$$

Mass of coarse aggregate (5-10 mm):

$$m = \rho \ x \, V$$

$$m = 2700 \, x \, 0.15266$$

$$m \ = 412.19 \, kg$$

Volume of coarse aggregate (10-14 mm):

$$V_{(10\text{-}14\text{mm})} = 0.16415 - (3.283 \, x \, 10^{-3}) \ = 0.160867 \, m^3$$

Mass of coarse aggregate (10-14 mm):

$$m = \rho \ x \, V$$

$$m = 2700 \, x \, 0.160867$$

$$m \ = 434.35 \, kg$$

Mass of Marble Dust:

Marble dust was used as an additive by weight of cement.

At P10M5:

$$M = 430 \, x \, 0.05 = 21.5 \, kg$$

At P10M10:

$$M = 430 \, x \, 0.10 = 43 \, kg$$

At P10M15:

$$M = 430 \, x \, 0.15 = 64.5 \, kg$$

Appendix B: Toughness

From the load-deformation curves obtained under compression, stress- strain graphs were obtained.

P40M5, specimen 1 is given as an example and the area under the curve was calculated from the equation (2) given below:

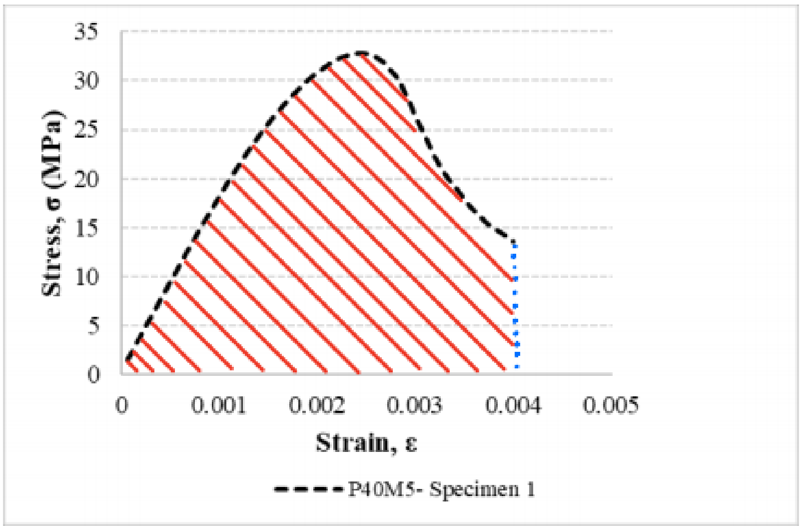


Figure 32: Stress-strain curve of P40M5 (specimen 1) under compression

$$\left[(\varepsilon_1 - \varepsilon_0)\ x \left(\frac{\sigma_0+\sigma_1}{2}\right)\right] + \dots\dots\dots\dots\dots\dots\dots\dots\dots \left[(\varepsilon_n - \varepsilon_{n-1})\ x \left(\frac{\sigma_{n-1}+\sigma_n}{2}\right)\right] \tag{2}$$

$$\left[(0.00006 - 0)\ x \left(\frac{1.538+0}{2}\right)\right] + \dots \left[(0.004 - 0.00397)\ x \left(\frac{13.611+13.802}{2}\right)\right]$$

Area under the curve= Toughness = **0.0846** N.mm/mm^3

Appendix C: Unit Weight of Concrete at High Temperatures

Table 16: Unit weight of unheated and heated concrete specimens

		Unit Weight (kg/m3)					
		60°C		**100°C**		**200°C**	
Mixture	**Sample**	**Unheated**	**Heated**	**Unheated**	**Heated**	**Unheated**	**Heated**
P0M0	1	2440	2430	2435	2415	2470	2390
	2	2425	2415	2440	2415	2470	2390
	3	2450	2440	2440	2415	2415	2340
	Average	2438	2428	2438	2415	2452	2373
P0M15	1	2465	2455	2470	2450	2465	2390
	2	2470	2460	2460	2435	2435	2365
	3	2480	2470	2480	2455	2490	2415
	Average	2472	2462	2470	2447	2463	2390
P10M0	1	2375	2365	2360	2340	2380	2300
	2	2380	2370	2375	2355	2365	2290
	3	2390	2380	2390	2370	2360	2285
	Average	2382	2372	2375	2355	2368	2292
P10M15	1	2405	2395	2390	2370	2405	2335
	2	2410	2400	2425	2405	2415	2340
	3	2410	2400	2415	2395	2415	2340
	Average	2408	2398	2410	2390	2412	2338
P20M0	1	2360	2350	2340	2320	2340	2270
	2	2315	2305	2330	2310	2315	2215
	3	2325	2315	2330	2310	2325	2235
	Average	2333	2323	2333	2313	2327	2240
P20M15	1	2370	2360	2355	2335	2375	2295
	2	2355	2345	2360	2340	2365	2270
	3	2365	2355	2370	2350	2360	2270
	Average	2363	2353	2362	2342	2367	2278
P30M0	1	2255	2245	2260	2240	2260	2155
	2	2265	2255	2275	2255	2250	2155
	3	2255	2245	2250	2230	2255	2155
	Average	2258	2248	2262	2242	2255	2155
P30M15	1	2330	2320	2330	2310	2345	2240
	2	2320	2310	2305	2285	2345	2245
	3	2320	2310	2345	2325	2350	2255
	Average	2323	2313	2327	2307	2347	2247
P40M0	1	2260	2250	2245	2225	2240	2145
	2	2250	2240	2250	2230	2255	2150
	3	2255	2245	2265	2245	2225	2125
	Average	2255	2245	2253	2233	2240	2140
P40M15	1	2295	2285	2310	2290	2290	2185
	2	2300	2290	2300	2280	2315	2215
	3	2310	2300	2315	2295	2325	2220
	Average	2302	2292	2308	2288	2310	2207