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STRENGTH AND DURABILITY OF COMPOSITE CONCRETES WITH MUNICIPAL WASTES

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ABSTRACT

The influence of different types of polyethylene (PE) substitutions as partial aggregate replacement of micro-steel fiber reinforced self-consolidating concrete (SCC) incorporating incinerator fly ash was investigated. The study focuses on the workability and hardened properties including mechanical, permeability properties, sulfate resistance and microstructure. Regardless of the polyethylene type, PE substitutions slightly decreased the compressive and flexural strength of SSC initially, however, the difference was compensated at later ages. SEM analysis of the interfacial transition zone showed that there was chemical interaction between PE and the matrix. Although PE substitutions increased the permeable porosity and sorptivity, it significantly improved the sulfate resistance of SCC. The influence of PE shape and size on workability and strength was found to be more important than its type. When considering the disposal of PE wastes and saving embodied energy, consuming recycled PE as partial aggregate replacement was more advantageous over virgin PE aggregate replaced concrete.

Keywords: chloride ion permeability; durability; fiber reinforced composites; municipal fly ash; self-consolidating concrete (SCC); sulfate attack; water-cementitious materials ratio; transport properties; waste management.

INTRODUCTION

In the last decades, sustainable development in the construction industry has been gaining increasing attention. Sustainable development can combine economic growth and environmental protection by conserving natural resources and saving embodied energy. Recycling of waste materials has been accepted as one of the most beneficial option to achieve sustainable development for construction industry[1]. Depending on the availability and price, several industrial wastes can be used as parts of the binder, i.e. cement and the filler (natural aggregate). For example, industrial by-products such as fly ash, municipal fly ash, ground granulated blast furnace slag and silica fumes have been used in construction industry as cement replacement or supplementary cementitious materials[1]. Recycled concrete[2] which is produced from demolishing concrete structures and recycled polymers[3] obtained from waste polymers are the most common wastes used as natural aggregate substitutes in the building industry[4,5].

Construction industry has been using recycled polymeric wastes as aggregate and fiber, because of its economic and ecological advantages[3,6-8]. Different types of polymeric wastes such as polypropylene (PP)[9,10], polyethylene (PE)[11-13], and polyethylene terephthalate (PET)[14-18] have been used as filler in concrete. However, most of these studies were conducted for conventional concrete and polymeric wastes were utilized as fine aggregate replacement. Therefore, little information is presently known regarding the use of polymers as coarse aggregate in the formulation of new concretes, especially self-consolidating concrete (SCC).

Qatar has been one of the largest producer and consumer of polymers in the Gulf region[19,20]. Effective disposal of polymeric wastes are constrained by its non-biodegradable nature and emission of dangerous gases when combusted. Therefore landfilling and incineration are not good alternatives for polymeric waste disposal. To solve the polymeric waste disposal problem, recycling has been supported by the Qatar government but still recycling is limited with small and private recycling plants[19].

Due to the rapid growth in the construction facilities, significant amounts of natural aggregate and cement are consumed in Qatar[21]. The quality and quantity of locally mined aggregates in Qatar is limited, therefore there is a shortage of raw material, especially for natural aggregate in the construction industry of Qatar[22]. In spite of scarcity of the natural resources, Qatar National Standards for Construction and Buildings (QCS) limits the amount of imported aggregates used in the construction facilities[23,24]. Therefore to sustain this requirement, creating new resources for aggregate and cement i.e. production of secondary raw materials is vital for construction industry of Qatar. Furthermore, cement production is known as one of the reasons of globally increasing CO_2[25] and so consumption of less cement could result less CO_2 emissions. To develop a sustainable construction industry in Qatar, natural aggregate and cement consumption should be reduced by replacing them with waste materials when it is applicable.

Self-consolidating concrete has several advantages with respect to conventional vibrated concrete, including, e.g., high workability, low segregation, no need for compaction, reduction in manpower and equipment[26]. In order to obtain these advantages, SCC needs more cement which in turn increases its cost and its impact on the environment due to CO_2 emission. Several studies in the literature showed that limestone powder, natural pozzolans, ground granulated blast furnace slag, silica fume and coal fly ash can be used in SCC to reduce the cement amount[27-32]. On the other hand, there are only few studies regarding the consumption of incinerator ashes in SCC in the literature. For example, Collepardi et al.[33] applied some pre-treatment methods for ground bottom ash (GBA) collected from Municipal Solid Wastes Incinerators (MSWI), used it in SCC and obtained good performance in terms of the mechanical and durability properties. Municipal fly ashes usually do not meet the required criteria of ASTM standards[34], they at least fail one or more criteria of the standards. Many studies in the literature showed that although municipal fly ash do not meet all the required criteria of ASTM standards, they can be utilized either in cement production or in conventional cement based materials for the benefits of environment and economy[35-46].

The main aim of this study is to determine the influence of incorporating different type of polyethylene in virgin and recycled form (QMW-derived) as 10% by weight of coarse aggregate replacement on the properties of micro-steel fiber reinforced SCC. And for the first time, the combination of the two by-products, silica fume and locally produced MSWI fly ash is utilized together to reduce the amount of cement and fine filler used to obtain SCC. The workability, mechanical and durability properties of cement-silica fume-MSWI fly ash SCC with respect to the type of PE are investigated. In addition, microstructures of hardened SCC mixtures are studied to examine the interaction between the PE and the matrix.

RESEARCH SIGNIFICANCE

On the one hand, the pressure from the growing scarcity of natural resources required for designing concretes, and on the other hand, the growing amount of domestic wastes collected by the municipal corporations of cities in the world presents a problem as well as an opportunity for engineers. Efforts to re-use useful domestic wastes in construction activities are gathering momentum worldwide. The current work focuses on understanding the mechanical and durability characteristics of steel fiber reinforced SCC using waste materials from Qatar municipal wastes (QMW).

EXPERIMENTAL PROGRAM

Material Properties

The cement used in all mixture was locally produced ordinary Portland cement (OPC) CEM I 42.5R which corresponds to ASTM Type I cement. Municipal Solid Waste Incinerator fly ash was collected from Qatar's Domestic Solid Waste Management Centre's (DSWMC) flue gas treatment system. DSWMC is a refuse-derived incineration facility in which municipal waste are pre-sorted to remove glass, plastics, ferrous and non-ferrous metals prior to incineration. After this pre-treatment, municipal waste is directly incinerated at a minimum temperature of 850^{o}C (1123^{o}K). Approximately 1500 tones of municipal waste is incinerated daily, of which 16% and 4% ended up as bottom ash and fly ash, respectively. For neutralization of acidic gases, lime is added in air pollution control units. Prior to the bag house filters, powdered active carbon is introduced into the flue gas stream[47].

The particle size distribution of OPC and MSWI fly ash were determined by laser diffraction technique and given in **Fig. 1**. Together with MSWI, silica fume (GMS85) was used in all mixtures. The particle size distribution of silica fume was not determined as it is already known that GMS85 silica fume is finer than both OPC and MSWI fly ash (99% of silica fume was reported ≤ 45 µm (1771 µin.) by the manufacturer). The chemical and physical properties of the cement, MSWI fly ash and silica fume are given in **Table 1**. The chemical compositions of silica fume was obtained from the manufacturer and those of cement and MSWI fly ash were measured using a wavelength-dispersive X-ray fluorescence (XRF) spectrometer, ZSX PrimusII, manufactured by Rigaku Corporation. The percentage of loss on ignition (LOI) at 750^{o}C (1023^{o}K) and specific gravity was determined according to ASTM C311 Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete[48].

The insoluble residue and fineness was measured according to ASTM C114[49] and ASTM C204[50], respectively.

As seen in **Table 1**, very low silica content of local MSWI fly ash may limit its consumption as pozzolanic material in concrete, while its high lime content may contribute to the cementitious properties[40]. Strength activity index (SAI) of MSWI fly ash with Portland cement was determined as 64%, which is less than the minimum requirement for pozzolanic material according to ASTM C618 Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete[51]. Therefore, in this study the main role of MSWI fly ash was to increase the fineness and cohesiveness of SCC, while silica fume was used as pozzolan.

The microstructure of the MSWI fly ash, PE aggregates and hardened SCC mixtures was investigated by scanning electron microscope (SEM), Quanta FEI 200 equipped with an Energy Dispersive X-ray (EDX) system for chemical analysis. The SEM image of MSWI fly ash (**Fig. 2**) indicated that unlike coal fly ash MSWI fly ash showed large fraction of non-spherical particles with heterogeneous particle size and morphology i.e. elongated, angular, very porous particles, and clusters of sintered particles.

Crushed limestone with a maximum size of 9.5 mm (0.374 in.) was used as coarse aggregate and river sand with a maximum size of 2.38 mm (0.0937 in.) was used as fine aggregate. The specific gravities of coarse and fine aggregates were 3.10 and 2.73, and water absorptions of 0.6% and 2.2%, respectively. A multi-carboxylate ether based superplasticizer (SP) with a specific gravity of 1.11 was used in all mixtures in order to obtain the self-consolidating concrete fluidity properties. Moreover, DRAMIX OL 6/16 straight cylindrical micro-steel fiber with a length of 6.00 mm (0.236 in.) and diameter of 0.16 mm (0.0063 in.) was used in all mixtures in order to compare the fiber reinforced property of the polyethylene fiber incorporated mixtures, the results of the comparison has been presented in another publication of the authors[52].

As plastic waste material, virgin high density polyethylene (v-HDPE) samples collected from Qatar Chemical Company (QCHEM) and virgin low density polyethylene (v-LDPE) samples collected from Qatar Petrochemical Company (QAPCO) (**Fig. 3**) were used in the mixtures in order to compare their effect on the workability, durability and mechanical properties of SCC. Both v-HDPE and v-LDPE was in the form of spherical granules with an average diameter of 3.0 mm (0.118 in.). Recycled polyethylene granules were collected from one of the plastic recycling companies in Qatar. In this plant, firstly HDPE and LDPE municipal plastic wastes were separated and then they were processed. Separated HDPE and LDPE wastes were washed and crushed into scraps. Prior to extrusion, these crushed scraps were dried and then fed into the extruder and extracted as plastic wires. Finally, these plastic wires were cut into cylindrical granules by cutter (**Fig. 3**). The average diameter and length were 4.0 mm (0.157 in.) and 3.5 mm (0.138 in.) for r-HDPE, and 3.0 mm (0.118 in.) of both for r-LDPE, respectively. The properties of polyethylene used in this research are given in **Table 2**, while the shape and size of polyethylene aggregates along with their SEM images are presented in **Fig. 3**.

Mixture proportions

Within the scope of experimental program, five concrete mixtures have been prepared and summarized in **Table 3**. The control mixture included OPC, MSWI FA, silica fume as cementitious materials and steel fiber. In the remaining mixtures, 10% by weight of coarse aggregate was replaced with virgin and recycled polyethylene granules. The partial PE substitution in this research kept 10% by weight as higher PE substitution rates were reported to decrease the mechanical strength of manufactured concrete drastically[11-13] while lower rates may not be feasible in terms of economy. For all mixtures, the amount of OPC, MSWI FA, silica fume, steel fiber and superplasticizer (SP) content were kept constant to reduce the number of cases to be studied in this study. As seen in **Table 3**, the only variable was the type of polyethylene aggregate substituted in the mixes 2-5.

SCC mixtures were prepared using an electrically driven concrete mixer. The preparation procedure was the same for all mixtures: firstly all aggregates (sand, coarse and PE), cement, MSWI FA, silica fume and steel fiber were mixed in a dry state. Then three quarters of mixing water mixed with the superplasticizer (SP) was added in the mixer and the mixture was mixed for 2 min period. The remaining water was added gradually into the mixture to provide uniformity in the mixture and mixed for a period of 2 more min. After completing the mixing procedure, fresh concrete tests including V-funnel, slump flow time and diameter and setting time tests were performed on the mixtures. From each concrete mixture, twelve Ø100x200 mm (Ø4x8 in.) cylinder specimens were cast for determination of compressive strength and permeability properties including water absorption, sorptivity and rapid chloride permeability tests, and six 160x40x40 mm (6.30x1.57x1.57 in.) beam specimens were cast for the determination of flexural strength, and nine 280x25x25 mm (11x1x1 in.) bar specimens were cast for sulfate exposure determinations in accordance with the related ASTM standards. Note that all specimens were cast in one layer without compaction as all mixtures were accepted as SCC. After 24 h, the specimens were demoulded and stored in water tank till the age of testing.

Tests on fresh concrete

Slump flow time (T_{50}), slump flow diameter (D) and V-funnel flow time was measured to assess the workability properties of SCC according to the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC)[53,54]. Slump flow diameter was used as an indication of the flowability of concrete when there was no blockage. Slump flow time was used to assess the viscosity and stability of SCC mixtures by measuring the time required for the mixtures to reach a 50 cm (20 in.) spread circle. Lower slump flow time can be used as an indication of greater fluidity and smaller workability loss. V-funnel flow test was used to determine the time required for a defined volume of SCC to flow through restricted spacing without blockage. As stated in the literature, good flowable and stable SCC mixtures would consume shorter time to flow out in V-funnel test[55,56].

Tests on hardened concrete

Tests performed on hardened concrete can be grouped into two as tests to evaluate mechanical and durability properties of SCC.

Mechanical properties

In order to determine mechanical properties, the compressive strength of SCC specimens was determined at 7, 28 and 90 days in accordance with ASTM C39[57] the flexural strength of SCC specimens was determined at 7 and 28 days in accordance with ASTM C293[58]. For mechanical tests, three specimens from each mixture was tested and average of these were calculated.

Durability properties

Permeability properties

To determine the permeability properties, 28 days age of Ø100x200 mm (Ø4x8 in.) cylinder specimens were cut into Ø100x50 mm (Ø4x2 in.) disc specimens and the absorption, sorptivity and rapid chloride permeability tests (RCPT) were performed on mentioned specimens. Water absorption which is defined as the amount of water absorbed under specified conditions was determined in accordance with ASTM C642[59]. As water absorption can only take place in pores which were emptied during drying and filled with water during the immersion period, water absorption indicates the degree of permeable porosity of a material.

The sorptivity was determined in accordance with ASTM C1585[60]. In this test, the rate of absorption of water by unsaturated SCC specimens were measured by the increase in the mass of a disc specimen at given intervals of time (1, 5, 10, 20, 30, 60, 180, 240, 300 and 360 min) when only one surface of the specimen was exposed to water, with the depth of water between 3 to 5 mm (0.12 to 0.20 in.).

The RCPT test was performed to determine the chloride permeability of 28 days SCC specimens in accordance with ASTM C1202[61]. At the end of this test, the total charge passed, in coulombs, is determined. Higher coulombs value indicates lower resistance to chloride ion penetration, while lower coulombs value indicates higher resistance.

Sulfate resistance

Sulfate resistance tests were performed on nine 280x25x25 mm (11x1x1 in.) bar specimens per mix. To determine the sulfate resistance, the bars were immersed into sulfate solution in accordance with ASTM C1012[62] and the length changes were measured at 1 week, 2 weeks, 3 weeks, 4 weeks, 8 weeks, 13 weeks, 15 weeks, 4 months and 6 months.

RESULTS AND DISCUSSIONS

Fresh concrete properties

The slump flow diameters of all mixtures were in the range of 595-670 mm (23.4-26.4 in.), slump flow times (T_{50}) were less than 5 s, and the V-funnel flow time were in the range of 5.47-7.11 (**Table 4**). Except the slump flow value, all the other fresh state properties met the EFNARC requirements[53,54]. The slump flow values of PE incorporated mixtures were less than the minimum requirement of the EFNARC which is 650 mm (25.60 in.). However, the minimum slump flow value is 550 mm (21.65 in.) for the American Concrete Institute (ACI)[63] and 500 mm (19.69 in.) for the Japan Society for Civil Engineers (JSCE)[64]. Moreover, since all the mixtures in this study filled the molds by their own weight without any vibration, and neither segregation nor considerable bleeding was visually observed in any of the mixtures during mixing, testing and casting, they were accepted as SCC. As seen from **Table 4**, addition of PE aggregates (Mix2-Mix5) slightly reduced the slump flow diameter and increased V-funnel flow time compared to the reference (Mix1). The lowering of workability was also reported in many studies incorporating several types of plastic aggregates[15,17,65,66] when larger replacement levels were used as in the current study (10% by weight). The reason behind this can be explained by the non/low-absorption characteristics of plastics which results in more free water, thus increases the porosity and eventually reduces the workability in fresh concrete[15,67].

Apart from the non-absorptive characteristics of PE, fresh properties of SCC was also influenced by the particle size of PE granules used in this study. Large and uniform size of PE granules (v-LDPE and v-HDPE: 3.0 mm (0.118 in.) and r-LDPE: 3.0 mm (0.118 in.) and r-HDPE: 4.0 mm (0.157 in.)) changed the granulometry of the aggregates, and resulted more empty spaces and voids in the fresh concrete and reduced the velocity of the flow of fresh SCC.

The same reason was also valid for V-funnel flow time in which flow of concrete was slightly blocked by large and uniform size of PE aggregates and hence increased the V-funnel time compared to the reference mixture (Mix1). While preparing the mixtures, the water content was adjusted to keep the same workability conditions in each SCC mixture. As seen in **Table 3**, the ratio of water-to-cementitious material (w/cm) was 0.49 for all mixtures, except Mix3. The w/cm ratio of Mix3 was 0.46 for similar workability characteristics. This could be explained by the smooth surface texture and spherical shape of v-HDPE[68](**Fig. 3**).

The type of PE aggregate had no significant influence on workability of SCC, so it can be concluded that addition of virgin/recycled LDPE and HDPE has no significant level of negative effect on the fresh properties of SCC when they were used as partial aggregate replacement from workability points of view.

Hardened concrete properties

Mechanical properties

The compressive strength and flexural strength test results were given in **Table 5**. As it was expected, PE aggregate substitution reduced the compressive strength, except Mix3, especially at earlier ages (7 and 28 days), but the difference was compensated at 90 days. For example, v-LDPE incorporated SCC mixture (Mix2) resulted in 37% strength reduction compared to the reference mixture (Mix1) at 7 and 28 days. While at 90 days, the strength of Mix2 was only slightly lower (20% in average) than the reference mixture. For all mixtures, PE incorporation resulted in slight strength reduction (≤20%) at 90 days age.

The reason for observing strength reduction in PE substituted mixtures could be the poor mechanical bonding between the cement matrix and surface of PE, which was also reported in other studies[11,17,65,69]. Considering the larger size of PE aggregate used, the impact of low surface energy of PE could be more pronounced in this study since low surface energy materials are very difficult to bond. Furthermore, hydrophobic nature of PE could also restrict the hydration of cement and hence contribute to strength reduction especially at earlier ages[12,65].

The compressive strength of all SCC mixtures was increased with age as shown in **Fig. 4-a**. SCC mixture containing v-HDPE (Mix3) showed slight increase in compressive strength (11% at 7 days and 14% at 28 days) compared to the reference mixture. The possible reason of this behaviour can be explained by the lower w/cm ratio of Mix3 which was 0.46. Smoother surface of v-HDPE seen from SEM image (**Fig. 3**) was the reason for a decrease in its w/cm ratio while keeping the same workability measures as the remaining mixtures.

Moreover, the results of flexural strength tests at 7 and 28 days were presented in Table 5. All SCC mixtures gained strength with age (**Fig. 4-b**). Like in compressive strength, reduction in flexural strength was also observed in SCC mixtures containing PE aggregates compared to the reference. The explanation reported for the decrease in compressive strength could be extended for the reductions observed in flexural strength. The reduction is more pronounced for SCC mixtures containing virgin PE aggregates than recycled ones. The results showed that incorporation of v-LDPE and v-HDPE decreased the flexural strength considerably (>30%) at 7 days, while at 28 days, flexural strength was only slightly lower (<20%) than the reference. Comparable flexural strength values were measured in SCC mixtures containing recycled PE aggregates. This was probably due to the cylindrical shape of recycled PE with length of 3.0 mm (0.118 in.) for r-LDPE and 3.5 mm (0.138 in.) for r-HDPE. A recent study by Yang et al.[67] regarding the use of recycled PET particles as sand replacement in SCC also reported that cylindrical shape can provide a bridging action and improve the toughness of concrete. Hannawi et al.[69] exhibited that for elongated plastic aggregates, flexural strength is improved with increasing plastic content. When considering the larger and cylindrical shape of recycled PE aggregates, we can conclude that recycled PE used in this study more likely acted as fiber reinforcement hence improved flexural strength compared to virgin PE aggregates. The length difference between r-LDPE and r-HDPE was 0.5 mm (0.02 in.). Longer size of r-HDPE may also be responsible for higher flexural strength of r-HDPE compared to r-LDPE. The influence of shape and size of plastic aggregates on mechanical properties of cement based composites have also been reported by some studies[68-70].

Durability properties

Permeability properties

The water absorption, sorptivity and chloride ion permeability tests performed at 28 days were reported for all SCC mixtures (**Table 5**). Water absorption values for all SCC mixtures were in the range of 5.7-8.5% and indicated low water absorption characteristic (less than 10%) which is in agreement with other SCC studies containing mineral admixtures[71,72]. As seen in **Table 5**, the water absorption capacity, namely permeable pore volume and the sorptivity values of all SCC mixtures with PE were higher than the reference mixture, except Mix3. Increase in total porosity with polymer addition was also reported by several studies[3,17,65,73,74]. The poor chemical bonding between PE and the cement matrix may lead to formation of micro cavities in the interfacial transition zone which in turn is responsible for increase in porosity. Excess gas trapped in the blend[75] due to uniform and large size of PE aggregates and hydrophobicity of PE could have also contributed to the porosity increase in mixtures containing PE. Contradictory to the above explanations, Mix3 showed lower permeable pore volume than the reference. The reason for having lower permeable pore volume in Mix3 was probably related with its lowest w/cm ratio as 0.46 among the all mixtures. The significant influence of w/cm ratio in SCC mixtures were also reported in the literature[76]. The reverse relation between strength and total permeable pore volume was clearly seen in **Fig. 5**, which also supports our previous statement. As well, for plastics with non/low-absorption characteristics, high plastic contents are resulted in more free water which surrounds and accumulates around the plastic aggregates and increases the voids and pores hence increases the water absorption [15,67,77]. In Mix3, w/cm ratio was lowest and this may be the reason of its lowest water absorption property among others.

As far as the sorptivity index was concerned, the reference mixture had the lowest sorptivity with a sorptivity index of 131x10^{-4} mm/$min^{1/2}$ (5.16 x10^{-4} in./$min^{1/2}$). As seen from **Table 5**, incorporation of PE, increased the sorptivity of the SCC mixtures (Mix2-5) about three times higher than the reference. This indicated that incorporation of PE as aggregate replacement has significant effect on the water sorptivity of SCC. The mechanism of increasing sorptivity can be explained by larger, permeable and connected pores in the PE substituted mixtures. However, further research should be conducted to establish the microstructure and the porosity structure of SCC mixtures incorporating PE substitutes.

The total charge passed from each SCC mixtures during RCPT test was presented in **Table 5**. Total charge passed was below 1000 Coulombs for all SCC mixtures, therefore all SCC mixtures were rated as “very low” according to limits suggested by ASTM C1012[61]. The main factors determining the resistance of SCC to chloride ion ingress are reported as binder type, binder content and admixtures[78-84]. In the current study, as seen in **Table 3**, all these variables (i.e. the amount of OPC, MSWI FA, silica fume and superplasticizer (SP)) were kept equal at each SCC mixture. Moreover, as stated by Teruzzi et al.[85] the interfacial zone between fibers/PE granules and cement paste may not represent a weak zone for ingress of detrimental agents. Considering all of these we can conclude that, regardless of the type of PE, there was no significant influence of partial PE aggregate substitution on the chloride permeability of SCC.

Sulfate resistance

The results of the length measurement of sulfate exposed bars at specified periods were illustrated in **Fig. 6**. Significant length change was measured for the reference mixture which did not have any PE aggregate. Regardless of the type of PE aggregate, all mixtures incorporating PE showed slight expansion under sulfate exposure conditions. The visual examination of all SCC mixtures showed slight visible deterioration at the corners and edges, but there were no clear difference between them. This emphasized that even with high sorptivity index, mixtures containing PE were more stable and durable under sulfate exposure conditions. Further research is needed to establish the influence of external sulfate exposure on the microstructure and pore networking of PE incorporated SCC.

Microstructural properties

The interfacial transition zone (ITZ) of the manufactured SCC mixtures and the cement paste in the ITZ were investigated by SEM-EDX and selected SEM images are presented in **Fig.7-I** and **Fig. 7-II,** respectively. As seen from the figure, the bonding between natural aggregate (N.A) and the cement matrix (**Fig. 7(a-I**)) was stronger than the bonding between PE aggregate and the cement matrix. The voids between PE aggregate and the cement matrix can be clearly seen in **Fig. 7(b,d,e-I)**. The composition of calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) could not be determined by SEM-EDX because of intermixing with other phases (i.e. the elemental ratio of Ca, Si, Al were not found to differentiate the C-S-H and CH). Therefore, the morphology was used to distinguish C-S-H and CH. The ITZ between natural aggregate and the cement matrix was characterised by the presence of large and dense C-S-H and CH crystals (**Fig. 7(a-II)**). While smaller CH crystals intermixed with C-S-H, unhydrated cement and MSWI FA was observed in ITZ of PE incorparated mixtures. (**Fig. 7(b-e,II)**). Among the SEM of PE incorparated SCC mixtures, C-S-H gel was only clearly seen in Mix3 (**Fig. 7(c-II)**). This dense and compact structure of C-S-H gel observed in Mix3 agreed with its low water absorption capacity and its higher strength, and hence confirmed our previous statemet and highlighted the influence of w/cm ratio on the strength of SCC. Moreover, some hydation products were observed on the surface of the PE aggregates (**Fig.7-I**). This indicated that there is a chemical interaction between PE aggregate and the cement matrix.

CONCLUSIONS

An experimental study is carried out to investigate the effects of incorporating different type of PE aggregates as partial aggregate replacement in SCC mixtures reinforced with micro-steel fiber. Workability properties of SCC mixtures in the fresh state and, mechanical and durability properties in the hardened state were discussed and the following conclusions were drawn from the present study:

- The uniform and large size of PE aggregates only slightly reduced the workability properties of SCC. The smooth surface texture and spherical shape of v-HDPE reduced the water requirement in Mix3 while satisfying the required workability parameters.

- Incorporation of PE aggregate as partial aggregate replacement resulted in slight reduction in compressive and flexural strength. The low bonding strength between the PE surface and the cement matrix was the main reason for strength reduction especially at earlier ages. The larger and uniform size of PE aggregate had also contributed this strength reduction, as well as restricted hydration of cement due to hydrophobic nature of PE especially at earlier ages.

- SCC mixtures incorporating recycled PE showed comparable flexural strength with the reference at 28 days. The cylindrical shape of recycled PE provided a bridging action and improved the toughness of SCC compared to virgin PE aggregates. This indicated the importance of PE’s shape and size on resulting mechanical properties.

- When evaluating the durability of SCC by its permeability properties as measured by absorption, sorptivity and rapid chloride permeability tests, partial substitution of natural aggregate with PE aggregates seemed to be beneficial and did not adversely affect the durability of SCC.

- In terms of the sulfate resistance, SCC mixtures were significantly durable under sulfate exposure when natural aggregate was partially replaced with PE.

- The microstructural analysis revealed a stronger adherence between the natural aggregate and the cement matrix, whereas voids in the ITZ confirmed the weak bonding between PE aggregates and the matrix.

- Observation of hydration products on the surface of PE aggregates indicated the presence of chemical interaction of PE with the cement matrix.

- However, further research on the microstructure and the porosity structure of SCC mixtures is desired to support the findings in this study.

From the above findings, it can be concluded that natural aggregate can be partially replaced with PE in SCC. There were no significant differences in fresh and hardened properties of SCC when different PE types used. Utilization of recycled PE can be more beneficial in terms of sustainability, conserving energy and reducing solid waste problem. Studies are currently underway to sense the distribution of stresses on the SCC composite beams under mechanical loading and the results will be reported in future. Further studies are required to improve the strength of PE incorporated SCC mixtures and for different sizes of the composite beams.

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Table 1– Chemical composition and physical properties of the Portland cement, MSWI fly ash and silica fume

Chemical Composition	OPC	MSWI FA	Silica Fume
CaO (%)	64.95	45.0	1.05
SiO_2 (%)	21.92	1.89	89.5
Al_2O_3 (%)	4.32	0.784	0.32
Fe_2O_3 (%)	3.78	0.601	0.38
MgO (%)	2.16	0.552	0.1
SO_3 (%)	2.08	8.67	0.1
Alkalies (Na_2O+ 0.658 K_2O) (%)	0.68	18.3	-
Loss on Ignition (%)	1.00	1.9	2.3

Insoluble Residue (%)	0.68	1.06	1.0
Physical Properties			
Specific Gravity	3.09	2.25	2.01
Blaine Fineness (cm^2/g)	3527	-	-

– = not measured items

Notes: 1 cm^2/g = 4.39 in.^{2}/oz.

Table 2 – Properties of polyethylene aggregates

	Polyethylene Type			
	v-LDPE	v-HDPE	r-LDPE	r-HDPE
Density (g/cm^3)	0.917	0.926	0.899	0.919
Load at Maximum Load (N)	27.45	33.12	33.20	74.34
Tensile Strength (MPa)	12	12.6	12.5	25.22
Elastic Modulus (MPa)	206	414	293	672
% Total Elongation at Fracture	382	136	348	152

Notes: 1 g/cm^3 = 0.578 oz/in.^{3}; 1 N = 0.2248 lb; 1 MPa = 145 psi.

Table 3 – Mixture proportions of SCC

Mix ID	Mix Design Label	W/CM[a]	Ingredient (kg/m^3)								
			Water	OPC	Silica Fume	MSWI FA	Aggregate			SP	Fiber
							Fine	Coarse	PE		Steel
1	Control	0.49	196	320	40	40	1012.1	831.2	-	12	16.6
2	v-LDPE	0.49	196	320	40	40	874.8	718.4	71.8	12	14.4
3	v-HDPE	0.46	184	320	40	40	876.4	719.7	72	12	14.4

4	r-LDPE	0.49	196	320	40	40	871.8	716	71.6	12	14.3
5	r-HDPE	0.49	196	320	40	40	874.8	718.4	71.8	12	14.4

[a] CM: cementitious material (OPC+ Silica Fume+ MSWI FA)

Notes: 1 kg/m^3 = 0.06243 Ib/ft.^{3}

Table 4 – Fresh properties of the SCC mixtures

Mix ID	Slump Flow		V-funnel flow time (s)
	D (mm)	T50 (s)	
1	670	2.39	5.47
2	595	2	7
3	595	2.26	7.01
4	615	3.14	7.11
5	615	2.36	6

Notes: 1 mm = 0.039 in.

Table 5 – Hardened properties of the SCC mixtures

Mix ID	Compressive strength (MPa)			Flexural strength (MPa)		Permeability Properties		
						Water absorption (%)	Sorptivity index (mm/min$^{1/2}$)	RCPT (Coulombs)
	7 days	28 days	90 days	7 days	28 days	28 days	28 days	28 days
1	17.5	24.8	32	8.5	9.4	6.8	0.0131	463
2	11.1	15.7	25.7	5.8	8.1	8.5	0.0323	460
3	19.4	28.2	31.3	5.5	7.4	5.7	0.0356	382

4	15.4	21.9	31.6	7.3	8.2	8.2	0.04545	470
5	15.5	22.9	26.7	7.5	10.2	7.8	0.03395	373

Notes: 1 MPa = 145 psi.; 1 mm/min$^{1/2}$ = 0.039 in. /min$^{1/2}$.

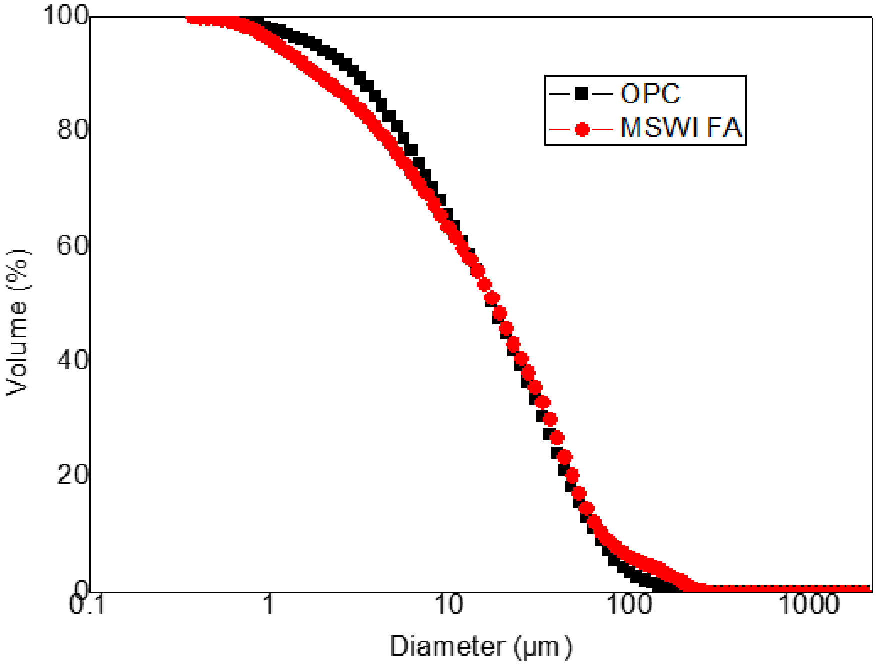


Fig. 1 – Particle size distribution of OPC and MSWI fly ash. (Note: 1 mm = 0.039 in.)

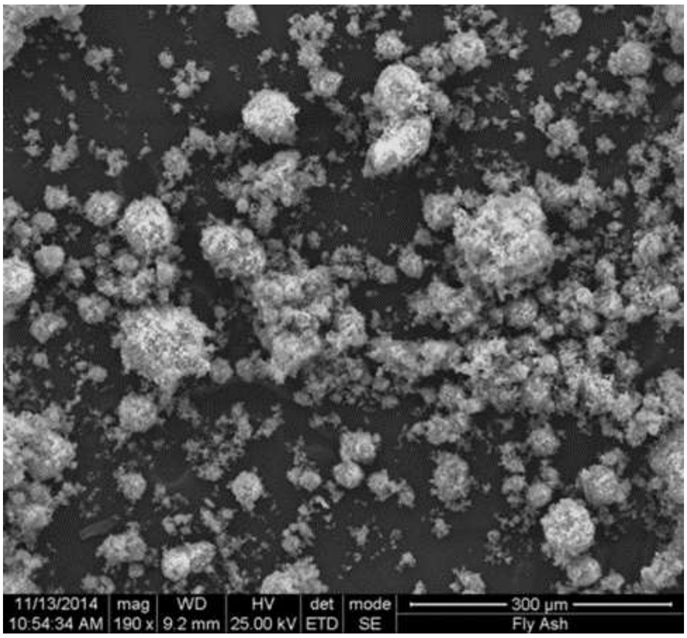
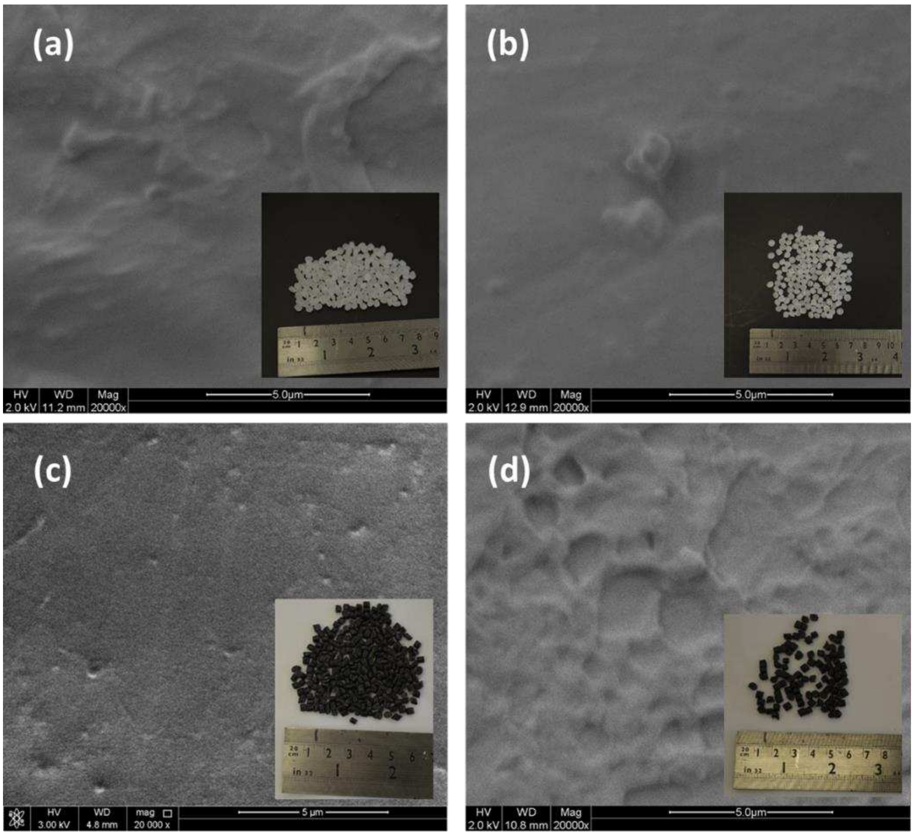


Fig. 2 – SEM image of MSWI fly ash.



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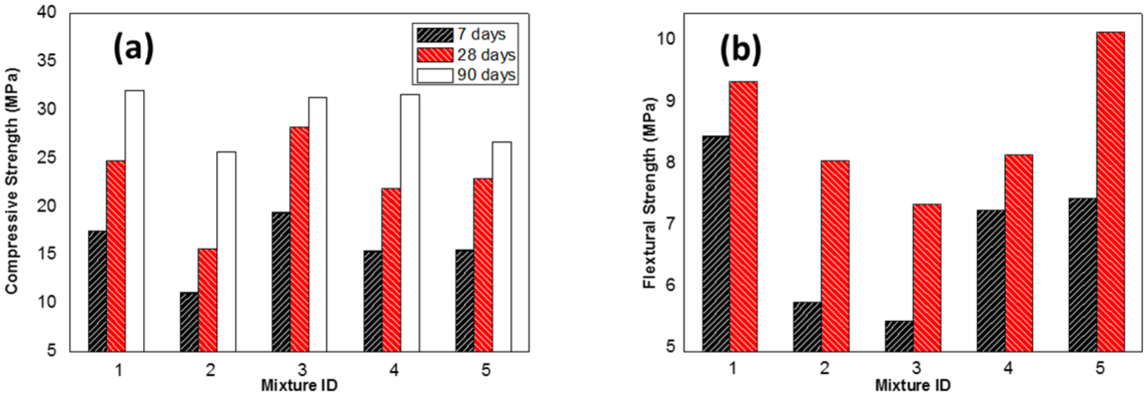


Fig. 4 – Strength development with curing age (a) compressive strength and (b) flexural strength. (Note: 1 MPa = 145 psi.)

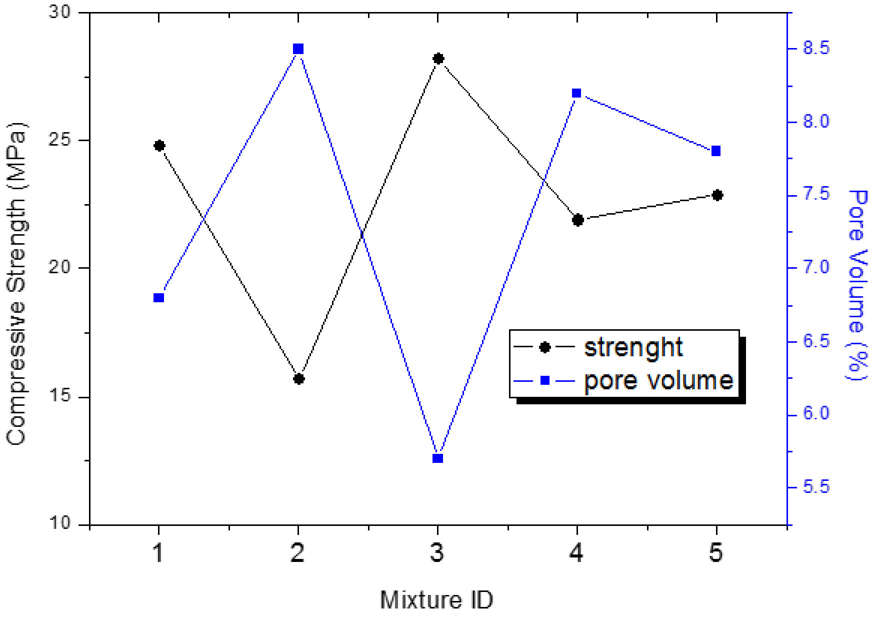


Fig. 5 – Relationship between compressive strength and permeable porosity. (Note: 1 MPa = 145 psi.)

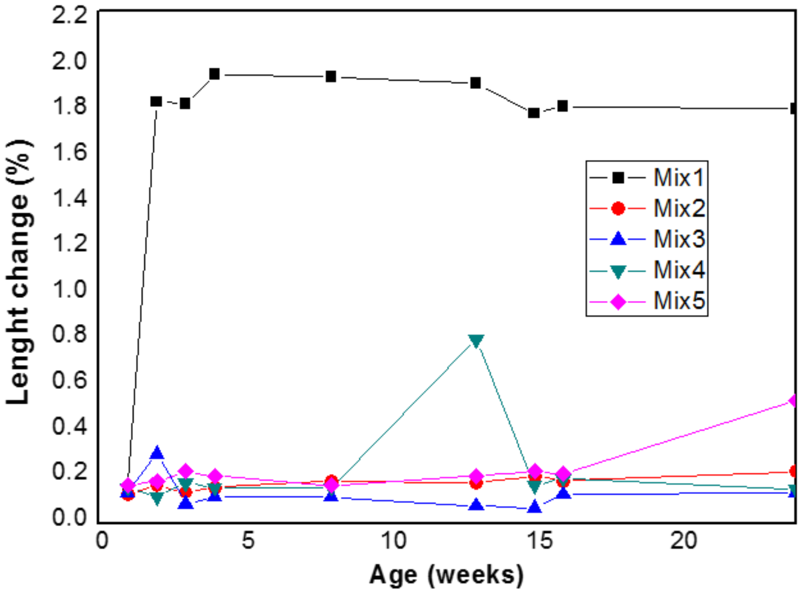
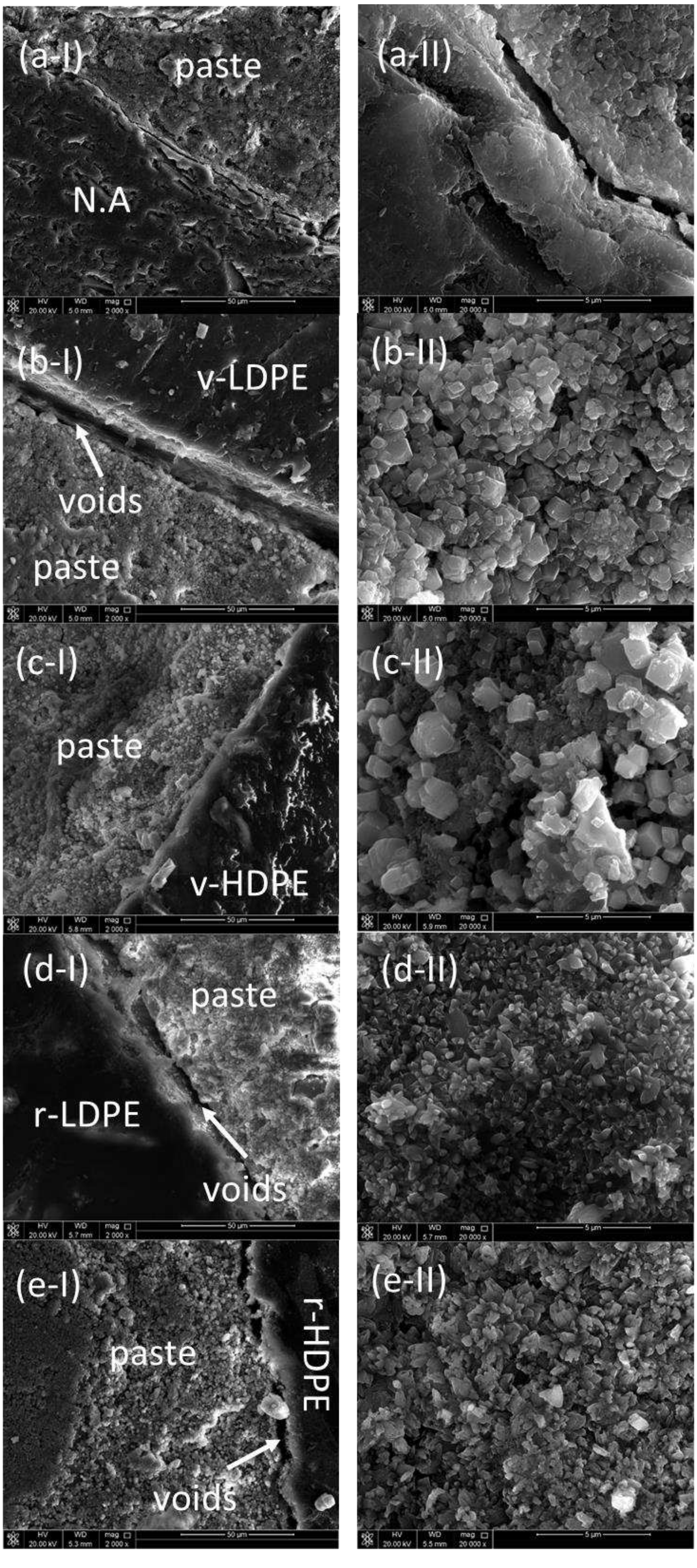


Fig. 6 – Length change under sulfate exposure.


(a-I)
paste
N.A
(a-II)
(b-I)
v-LDPE
voids
paste
(b-II)
(c-I)
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v-HDPE
(c-II)
(d-I)
paste
r-LDPE
voids
(d-II)
(e-I)
paste
r-HDPE
voids
(e-II)

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