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DOI:
10.1061/(ASCE)MT.1943-5533.0001765

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Alqahtani, F, Khan, MI, Ghataora, G & Dirar, S 2017, 'Production of Recycled Plastic Aggregates and its Utilization in Concrete', *Journal of Materials in Civil Engineering*, vol. 29, no. 4, 04016248. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001765

Link to publication on Research at Birmingham portal

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Download date: 26. Aug. 2022

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Production of Recycled Plastic Aggregates and its Utilization in Concrete

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ABSTRACT

Plastic represents an environmental issue, as only 7% of it is recycled. The plastic remaining is either burned, disposed of in an uncontrolled manner or landfilled. Thus, in order to reduce the quantity of plastic which is disposed of, there is a need to increase the amount of the material which enters various product streams. This includes its use in the construction industry, and more particularly in concrete, which utilises very large quantities of aggregate. A novel aggregate (RPA) comprising recycled plastic was developed. The aggregate produced was lightweight, with a density ranging from 510 to 750k kg/m^3 and absorption of from 2.7 to 9.81%. Other properties were comparable to aggregates of similar densities. Various composition RPA was used in concrete and the resulting properties of both fresh and cured concrete were measured. For a given w/c ratio, it was possible to achieve slump of between 40 and 220 mm and fresh density of between 1827 and 2055 kg/m^3. Further, 28-day strengths of between 14 and 18 MPa were achieved. Flexural strength was also measured. SEM analysis was undertaken to view the structure of the aggregate and the interface between the RPA and the cement matrix.

Keywords: LLDPE; Filler; RPA; LWA; Lightweight concrete; SEM.

Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS EN	British Standards and European Standards
CH_3	Methyl
CIO_2	Chloride dioxide
CO	Carbon monoxide
CO_2	Carbon dioxide
FAA	Fly ash aggregate
FE-SEM	Field emission scanning electron microscopy
GBFS	Granulated blast-furnace slag
HC’s	Hydrocarbons
HCN	Hydrogen cyanide gas
HDPE	High density polyethylene
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
LWA	Conventional lightweight aggregate
LWC0.5	Concrete made using conventional lightweight aggregate (LWA) at (w/c=0.5)
LWC0.6	Concrete made using conventional lightweight aggregate (LWA) at (w/c=0.6)
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
PC	PET plastic coarse particles
PET	Polyethylene terephthalate

PF	PET plastic fine particles
PP	PET plastic pellet particles
PS	Polystyrene
RPA	Recycled plastic aggregate
RP1F1A	Recycled plastic aggregate made using 50 % LLDPE and 50 % red/dune sand
RP1F2A	Recycled plastic aggregate made using 50 % LLDPE and 50 % fly ash
RP1F3A	Recycled plastic aggregate made using 50 % LLDPE and 50 % quarry fines
RP2F1A	Recycled plastic aggregate made using 30 % LLDPE and 70 % red/dune sand
RP2F2A	Recycled plastic aggregate made using 30 % LLDPE and 70 % fly ash
RP2F3A	Recycled plastic aggregate made using 30 % LLDPE and 70 % quarry fines
RP1F1C0.5	Concrete made using recycled plastic aggregate (RP1F1A) at (w/c=0.5)
RP1F2C0.5	Concrete made using recycled plastic aggregate (RP1F2A) at (w/c=0.5)
RP1F3C0.5	Concrete made using recycled plastic aggregate (RP1F3A) at (w/c=0.5)
RP2F1C0.5	Concrete made using recycled plastic aggregate (RP2F1A) at (w/c=0.5)
RP2F2C0.5	Concrete made using recycled plastic aggregate (RP2F2A) at (w/c=0.5)
RP2F3C0.5	Concrete made using recycled plastic aggregate (RP2F3A) at (w/c=0.5)

RP1F1C0.6	Concrete made using recycled plastic aggregate (RP1F1A) at (w/c=0.6)
RP1F2C0.6	Concrete made using recycled plastic aggregate (RP1F2A) at (w/c=0.6)
RP1F3C0.6	Concrete made using recycled plastic aggregate (RP1F3A) at (w/c=0.6)
SEM	Scanning electron microscopy
SLA	Synthetic lightweight aggregate
W/C	Water to cement ratio
WPLA	Waste plastic lightweight aggregate

Introduction

Rapid industrialization and the development of a throw-away culture has led to waste handling and disposal problems. Rapid growth is impacting on virgin materials, which are available only in limited quantities. This pressure on finite resources and burdensome waste is leading to both economic and societal pressures, driving the need to recycle waste (Pappu et al. 2007). In order to facilitate development of a culture where sustainable use of materials is synonymous with development, increasing political pressure is brought to bear on manufacturers through national standards, incentivizing the use of waste and secondary materials (Pappu et al. 2007; Siddique et al. 2008).

The problem of waste products is of major concerns around the globe. However, plastic waste is a material which has potential for recycling in various products (Pappu et al. 2007; Siddique et al. 2008). Worldwide plastic production in 1950 was 1.7 Mt, but this had jumped to 313 Mt in 2014, which is approximately a 184-fold increase (Statista 2014). Polyethylene based products form the largest percentage of waste from this, at about 29% of total waste plastic (DG Environment 2011). These include low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and high density polyethylene (HDPE). Polyethylene terephthalate (PET) and polypropylene amount to 20% and 18% respectively of global plastic waste, and other polymer types represent about 33% (DG Environment 2011).

Plastic wastes are divided into two categories; i.e. recyclable and non-recyclable, and only 7% of these wastes are recycled in the UK, whereas 8% are directly burned and 80% sent to landfill (Siddique et al. 2008; Statista 2014). In fact, the recycling percentage for plastic is very low, due to environmental, economic and social impacts. For instance, burning polymers results in toxic gas emissions including CO_2, CO, CH_3, HC's, HCN, ClO_2, NO and NO_2, which pollute the environment (Junod 1976). Furthermore, the cost of products incorporating waste plastic can be more than those produced from virgin plastic due to the additional cost of recycling. It is worth noting that the quality of recycled plastic may not be compatible with virgin plastic after passing through various recycling processes. This further limits opportunities to incorporate such materials into products. Similarly, contaminated plastic products cannot be recycled due to their potential hazards and harmful gases which can have serious implications for society (Statista 2014). Additionally, sending waste plastic to landfill or burning it is not an efficient solution because the evolution of toxic and hazardous gases can cause serious issues for surrounding areas. Therefore, there is an urgent need to explore various ways of utilizing waste plastic products in an efficient and economical manner. One of the options in this regard is to utilize this plastic waste in the form of aggregates in the production of concrete.

Plastic has been used in concrete shredded or has been mixed with other materials to form an artificial or synthetic aggregate. It should be noted that aggregates amount to about 60-70% of the total mass of concrete, and replacing natural aggregates either partially or fully with waste plastic aggregates will help preserve natural resources. This argument is emphasized by the fact that global consumption of aggregate is expected to exceed 48.3 billion metric tons by 2015 (Fredonia 2012). Since plastics have lower density than most natural materials, they can therefore be readily used to form lightweight aggregates which may replace naturally existing aggregates of similar density.

However, the use of plastics as aggregate in concrete significantly reduce its workability and strength properties dependent on the replacement level (Rahman et al. 2012; Yazoghli-Marzouk et al. 2007; Ismail and Hashmi 2008; Saikia and de Brito 2014; Rahmani et al. 2013; Hannawi et al. 2010; Albano et al. 2009; Saradhi Babu et al. 2005; Akçaözoğlu et al. 2010; Wong 2010; Batayneh et al. 2007; Al-Manaseer and Dalal 1997).

For example, many researchers (Saikia and de Brito 2014; Rahmani et al. 2013; Albano et al. 2009; Ismail and Hashmi 2008) found that reductions in workability and 28-day compressive strength vary from 43% to 95 % and from 9 % to 62 % respectively, as the percentage replacement of shredded PET plastic with sand increases from 0% to 20%. Hannawi et al. (2010), together with other researchers (Yazoghli-Marzouk et al. 2007; and Akçaözoğlu et al. 2010) found that reductions in 28-day compressive and flexural strength vary from 50 % to 90 % and from 17.9 % to 88 % respectively when increasing the replacement percentage of PET from 0 % to 100 %. Moreover, the lower replacement levels of WPET of 5% have caused insignificant reduction in both compression and splitting tensile strength (Frigione 2010).

Other work (Wong 2010; Batayneh et al. 2007; Al-Manaseer and Dalal 1997) has found that reduction in 28-day compressive strength varies from 11 % to 72 % as the percentage replacement of mixed waste plastic with sand or aggregate increases from 0 % to 50 %. Rahman et al. (2012) and Babu et al. (2005) demonstrate that reduction in 28-day compressive strength varies from 77 % to 94 % corresponding to increasing Expanded Polystyrane (EPS) as an aggregate replacement from 0 % to 95 %. Meanwhile, Panyakapo and Panyakapo (2008) found that 28-day compressive strength was reduced by 24 % as the replacement percentage of melamine waste with sand was increased from 0.5 % to 1 %. A recent study reported by Gu and Ozbakkaloglu (2016) also supports the above-mentioned drawbacks of using plastic as aggregate in concrete.

Some concrete produced with a conventional lightweight aggregate has been shown to exhibit excessive shrinkage and high water absorption (Kohno et al. 1999; Blanco et al. 2000; Rossignolo and Agnesini 2002). This is particularly the case with lightweight aggregate (of volcanic origin) available on the Arabian Peninsula. Meanwhile, economic growth in this region has led to high demand for concrete products, and this has generated a large demand for aggregates. Furthermore, demand is strong for materials which can provide good insulation (due to the hot climate) and which have suitable structural elements for offshore oil production. However, the LWA concrete produced from volcanic rock is associated with problems such as low strength, lack of durability, high mining and hauling costs, excessive drying shrinkage, high water absorption and lack of local capacity (Choi et al. 2005; Choi et al. 2009).

Therefore, to overcome the problems associated with concrete produced with conventional LWA, the use of synthetic aggregates with lesser weight and absorption as well as improved insulation properties will be beneficial for the Gulf region in reducing energy costs. The use of synthetic lightweight aggregate in concrete will reduce CO_2 emissions, as lighter materials result in smaller element sections which ultimately require less cement (Choi et al. 2009). Additionally, using synthetic aggregates in concrete can decrease landfill disposal and save natural resources.

Although extensive research has been carried out on the use of recycled plastic in concrete as a direct replacement for natural/conventional lightweight aggregates (Rahman et al. 2012; Yazoghli-Marzouk et al. 2007; Ismail and Hashmi 2008; Frigione 2010; Saikia and de Brito 2014; Rahmani et al. 2013; Hannawi et al. 2010; Albano et al. 2009; Saradhi Babu et al. 2005; Akçaözoğlu et al. 2010; Wong 2010; Batayneh et al. 2007; Al-Manaseer and Dalal 1997), far less research has been conducted on the use of plastic-based aggregate in concrete as an indirect replacement (Kashi et al. 1999; Jansen et al. 2001; Malloy et al. 2001; Phillips and Richards 2004; Dunster et al. 2005; Swan and Sacks 2005; Choi et al 2005; Choi et al 2009).

Plastic aggregates such as Plasmatex© and Plasmega© have been produced from shredded mixed plastic waste and secondary aggregates (Phillips and Richards 2004; Dunster et al. 2005). These aggregates range in size from 5mm to 50mm (Phillips and Richards 2004). Similarly, synthetic lightweight aggregates (SLAs) have been produced from a mix of fly ash and plastics such as polystyrene (PS), low density polyethylene (LDPE), high density polyethylene (HDPE), and a mixture of various plastics (MP) (Kashi et al. 1999; Jansen et al. 2001; Malloy et al. 2001; Swan and Sacks 2005). SLAs have also been produced at different fly ash: plastic ratios, ranging from 0:100 to 80:20, and natural aggregate then replaced with SLA in concrete and pavement systems. The results of these studies show that at 80% fly ash, the unit weight, slump, compressive strength and split cylinder tensile strength of concrete using SLA were reduced by about 15%, 16%, 43% and 26.4% respectively, compared to conventional concrete (Kashi et al. 1999; Jansen et al. 2001).

Waste plastic lightweight aggregate (WPLA) was also produced from polyethylene terephthalate (PET) with granulated blast-furnace slag (GBFS) and river sand aggregate (Choi et al. 2005). The outcome revealed that at a replacement level of 75% of WPLA aggregate, the slump of WPLA concrete increased by 51%, while the density, compressive strength, splitting tensile strength, modulus of elasticity, and structural efficiency were reduced by 31%, 33%, 43%, 28% and 23% respectively, compared to normal concrete (Choi et al. 2005; Choi et al. 2009). On the other hand, use of LLDPE is less investigated compared to other types of plastics from the polyolefin group. Therefore, the authors of the current work (Alqahtani et al. 2015) investigated the effect of using recycled plastic aggregate (RPA) as a total replacement for LWA on the durability of concrete using a chloride permeability test. They conclude that the 28-day compressive strength and chloride permeability of RPA concrete is reduced by 48 and 15% respectively as compared with LWA concrete.

This study outlines the manufacture of a novel RPA made from LLDPE and different types of fillers (red sand, fly ash and quarry fines). In addition, this study presents the possibility of using RPA as a total replacement for conventional coarse LWA in concrete. The effect of RPA on fresh and hardened concrete properties at different w/c ratios was investigated.

Materials and methods

Materials

The basic materials used to produce RPA were polymer and filler. The plastic (LLDPE) used was supplied in powdered form by local supplier who collects all types of waste plastics from local vicinity and treats them. The treatment process starts from collecting, purifying, shredding, melting, pelletized and then powdered in the final form. The unit weight of polymer (LLDPE) used was 918 kg/m^3. Fillers included red sand, fly ash and quarry fines with median particle size 186.37, 6.14 and 19.27µm respectively, as shown in the particle size distribution curve in Figure 1. Conventional Portland cement was used in this investigation. The specific gravity and fineness of cement were 3.15 and 3500 cm^2/gm, respectively. For the preparation of control mixes, conventional coarse LWA which was collected from the western region of Saudi Arabia was used in this investigation. The nominal maximum size of conventional LWA (volcanic rock based) used was 10 mm. The physical properties of the conventional LWA, red and crushed sand used in this study are shown in Table 1. The fine aggregate used was a combination of 65 % red sand and 35 % crushed sand in order to satisfy the ASTM C136 standard as shown in Figure 2. The key material in this study was the RPA discussed below, which was produced and then used to replace local lightweight coarse aggregate in concrete. Physical properties and the gradation curve of these aggregates are shown in Table 3 and Figure 3 respectively, in Subsections 2.2 and 3.1 respectively.

Manufacture of recycled plastic aggregate

Different types of granulated recycled plastics which were made originally from LLDPE were mixed with red sand (dune sand), fly ash and other granular materials such as quarry fines to form aggregates that had potential for use in concrete. The properties of LLDPE and filler used were investigated and reported in previous material section above. LLDPE was mixed at 30% and 50% with three different types of fillers to prepare the synthetic recycled plastic aggregate. Fillers included red sand or different types of granular waste such as fly ash or quarry fines. Compositions of mixtures are shown in Table 2. Aggregate samples are identified by a name of the format RP_xF_yA, where RP_x identifies the recycled plastic type and percentage, F_y identifies the filler type and percentage, and A represents the aggregate (e.g., RP1F1A - RP_1 denotes 50% recycled LLDPE plastic, F_1 stands for 50% red sand filler, and A represents aggregate).

The process of making RPA involves mixing plastic with filler to form a homogenized mixture, compressing the homogenized mixture in a mold, melting the plastic in the homogenized mixture to form a composite sheet or slab, and shredding the composite sheet or slab to form either coarse or fine aggregates for use in making concrete. The production of the aggregate is described in more detail elsewhere (Alqahtani et al. 2014).

The novel aggregate RPA with different grain size, shapes and textures is shown below in Figure 4. The physical properties of RPA were evaluated in accordance with ASTM C 330-04 as shown in Table 3 and discussed in Section 3.1. In addition to this, Scanning Electron Microscopy (SEM) and ash tests were conducted to assess the uniformity of the mixture between the polymer and filler. The SEM analysis was done by preparing three samples of Polymer/red sand (RP_1F_1A) aggregate composite sheets for surface and cross-sectional morphology examination. The ash content test was conducted to determine the amount or percentage of filler existing after the test because plastic burns off during the test in accordance with ASTM D2584. A detailed description and discussions are presented in Section 3.1.

Mixture proportions

The design of the mix of the RPA and LWA concrete was developed in line with the ACI 211.2-98. For the mixes comprising RPA, the amount of coarse aggregate for RPA was calculated by using the specific gravity of the RPA as a replacement for the specific gravity of the conventional LWA. The mixed proportions are shown in Table 4. Eleven concrete samples were produced at water cement ratios of 0.50 and 0.60. For the RPA concrete, the replacement of LWA with RPA was 100%. Concrete samples are identified by a name of the format RP_xF_yC, where “RP_xF_y” identifies the RPA type and “C” represents the concrete (e.g., RP1F1C - RP_1F_1 means RPA produced using 50% recycled LLDPE plastic and 50% red sand filler, and C represents concrete).

Testing

The experimental investigation compared the fresh properties, hardened properties and microstructure analysis of RPA concrete with LWA concrete. The fresh concrete properties, including slump and fresh density, were examined according to ASTM C143 and ASTM C138 respectively. Dry density of cured concrete was measured at 28 days of water curing, in line with BS EN 12390-7:2009. Concrete compressive strength and flexural strength tests were conducted in accordance with ASTM C579−01 and ASTM C580−02 standard procedures at 7, 14 and 28 days of water curing.

The average of three specimens at each age was taken for compressive and flexural strength results. The variation between the results at each age was within ±5% of the mean value (i.e. compressive strength for LWC0.5 at 28 days were 29.02, 31.34, 29.91 so the mean is equal to 30.09, variance is equal to 1.17, standard deviation of the mean is equal to 0.6755, so the results for compressive strength of LWC0.5 is equal to 30.09 ± 0.7). Therefore, the mean values of three measurements were taken as the result. Additionally, a detailed analysis of the aggregate and concrete was performed using an FE-SEM (field emission scanning electron microscope) versa 3D. SEM imaging was performed to explain the microstructure and mode of failure of the concrete.

Results and Discussion

Recycled plastic aggregate investigation

The results for the RPAs as summarized earlier in Table 3 show that RPA had a nominal maximum size of 10mm. The particle shapes of RPAs produced using red sand, fly ash and quarry fines were sub-angular, sub-rounded and angular respectively, whereas surface textures of RPAs with red sand, fly ash and quarry fines were partially rough, smooth and rough, respectively. The aggregate's shape and texture significantly affects workability and other fresh and hardened concrete properties. For angular and rougher aggregate, the bonding between cement matrix and aggregate is enhanced. Rahmani et al. (2013) observe that bonding is adversely affected by smoothness of aggregate texture. Similarly, Panyakapo and Panyakapo (2008) reported that bonding was improved due to the roughness of aggregate particle texture. The latter point also has been reported by Kaplan (1959), who pointed out that the interlocking between coarse aggregate and cement paste can be enhanced with rougher particle texture, which ultimately improves the mechanical properties of the concrete.

Likewise, the aggregate grading has a vital effect on both fresh and hardened concrete properties. For example, well graded aggregate provides better workability and strength in contracts with poorly graded aggregate. Also, the amount of cement paste needed for bonding in the case of well graded aggregate is less compared with the poorly graded case. Therefore, the sieve analysis was conducted and results plotted in Figure 3. The tested aggregates (RPA and LWA) can be classified as per the sieve analysis into three groups as follows as shown in Figure 3:

Group 1 which completely satisfy the ASTM 330-04 (i.e. within standard limits) such as (RP1F2A, RP1F3A and RP2F2A);

Group 2 which deviated by 41% from the maximum permissible limits of lower sieve size such as (RP2F3A). This is due to the fineness of the quarry fine filler compared to other types of fillers;

Group 3 which deviated from the minimum permissible limits of upper sieve by 32 % and 26 % for RP1F1A and RP2F1A respectively .This is because the particle size of the red sand filler was coarser when compared to other types of fillers. Similarly, LWA is deviated by 39 % from the minimum limits of upper sieve.

Therefore, the RPA aggregate manufactured using red sand filler was coarser, whereas RPA formed using quarry fines was finer as compared with other types of RPA. Similarly, the fineness modulus of the RPA marginally decreased with the increase in filler percentage (from 50% to70%). However, the fineness modulus slightly decreased, by 2.7%, 9.8% and 10.1%, as compared to the conventional LWA at the 70% filler percentage. The fineness modulus of RP1F1A was the highest among all samples due to the large size of particles of the red sand filler (as mentioned above) compared to other types of fillers. Meanwhile, RP2F3A was the lowest among all RPAs, indicating that its particles were finer. Therefore, the finer aggregate may adversely affect workability but may also enhance compressive strength.

The unit weight of the RPA indicated a 20%, 0.5%, and 3.5% increase with incorporation of each filler (red sand, fly ash, and quarry fines) with the increase in filler percentage (from 50% to 70%). However, when compared with conventional LWA, the general trend for the unit weight of RPA revealed a significant decrease in unit weight as compared to conventional LWA, with the exception of RP2FIA's unit weight, which showed an increase. The unit weight reduction of RP1FIA, RP1F2A, RP1F3A, RP2F2A and RP2F3A was 14%, 23%, 27%, 22.5% and 10% respectively, while RP2F1A's unit weight increased insignificantly, by 7% as compared to conventional LWA. This reduction in the unit weight of the RPA compared to conventional LWA was due to the lighter weight of the plastic and the filler, as well as an average 5% increase in void ratio as compared to conventional LWA. A reduction in unit weight reduces the overall weight of the structure, which can result in cost savings.

The water absorption of RPA was lower as compared to conventional LWA. Water absorption reduction for RP1FIA, RP1F2A, RP1F3A, RP2F1A, RP2F2A and RP2F3A was 85%, 66%, 68%, 84%, 51% and 47% respectively, as compared to conventional LWA. The reduction in water absorption of RPA observed would resolve the high water absorption associated with conventional LWA, as it would require less water when making the concrete, as little is absorbed by RPA. In addition, the increase in filler (red sand, fly ash, and quarry fine) percentage from 50% to 70% increased water absorption by 1.5%, 33.36% and 39.34%, respectively. This is because the plastic had no water absorption capability, while the trace increase in absorption of RP1F1A and RP2F1A compared to other RPAs was due to the red sand filler being less absorbent.

Aggregate strength was also measured using an impact value test. The test findings show that the impact value of LWA is 39 %, while RPA strength cannot be measured using this test. This is because RPA is not crushable due to the plastic nature of its matrix, as confirmed in Figure5. Additionally, Scanning Electron Microscopy (SEM) investigation of RPA samples demonstrated uneven distribution of filler particles, with concentrated regions of finer particles, and a few coarser particles. Cross-sections of samples confirmed non-uniform distribution, as shown in Figure 6, with fractured, pebble-shaped filler particles in a plastic matrix. This was expected behaviour as two dissimilar constituents were mixed. Also it is clear from Figure 6 that the fly ash particles are loose at the surface, which might prevent or weaken the bond between RPA particles and the cementious matrix.

Finally, the Ash test results for three different samples of RP_1F_1A represent the degree of homogeneity of the mix comprising the polymer (LLDPE) and filler (red sand) which exists after the test. The three tests showed a variation of approximately ±8% relative to the mean value. To confirm homogeneity of RPA for aggregate, the results of three samples for each mix at different ages should provide less variation. Similarly, non-homogenous RPA aggregate should provide high variation between three samples. Therefore, the results of three samples of each test confirmed the lower variation which is repeatedly observed at all ages. It seems that in terms of the overall performance of the concrete, the mixing of different components to form the aggregate was adequate.

Concrete investigation

Fresh properties

The fresh properties of RPA concrete examined included slump and fresh densities. Results are tabulated in Table 5. Results show that the slump of RP1F2C0.5 was 9% higher and that of RP2F3C0.5 was about 80% lower compared to LWA concrete. The increase in slump for RP1F2C0.5 was attributed to the sub-rounded particle shape and smooth surface texture of RPA containing fly ash filler, and also to the fraction of loose particles as mentioned earlier and shown in Figure 4. The low amount of slump in RP2F3C0.5 was ascribed to the friction caused by the angular particle shape and rough surface texture of RPA with quarry fines as filler. Additionally, due to the overall well graded grain size distribution; the slump of concrete made with RPA with red sand (i.e. RP1F1C0.5 and RP2F1C0.5) achieved the targeted slump (75-100mm). Similarly, the slump of the RP1 group concretes was 21%, 9%

and 53% higher than the RP2 group concretes made with RPA using red sand, fly ash and quarry fine fillers respectively.

It can be concluded that the slumps for RPA concrete made with red sand and quarry fines fillers (RP1F1C0.5, RP1F3C0.5, RP2F1C0.5 and RP2F3C0.5) were 52.5 %, 57.5 %, 62.5 % and 80 % lower than the conventional one. This trend was in agreement with previous work carried out by Jansen et al. (2001) and Kashi et al. (1999), who concluded that slump of SLA concrete made with 80 % fly ash was reduced by 16 %. On the other hand, for concrete with RPA produced with fly ash particles (RP1F2C0.5), the slump was marginally increased, by 9 %. This trend is similar to that seen by Choi et al. (2009) and Choi et al. (2005), who reported that the slump of concrete made with WPLA at 75 % replacement was significantly increased, by 51 %.

Additionally, the slump results showed that with an increase in water-cement ratio of 0.1, the slump of concrete produced using RPA containing fillers of red sand, fly ash, and quarry fine increased by 46%, 8%, and 41%, respectively, whereas the conventional LWA concrete had a nominal increase. The reason for this is that a lower amount of cement requires less water for interaction, leaving more free water. The same finding was observed by Rahmani et al. (2013). However, with respect to the cement amount, two water contents was exist. The mixtures with high water content provided higher slump. Also, it is inferred from the results that the effect of an increase in the water/cement ratio of 0.1 is less prominent in conventional LWA concrete as compared to RPA concrete. However, the slump of RPA concrete was less than LWA concrete at the same w/c ratio.

Similarly, the fresh density of RPA concrete was reduced (the highest reduction was 10% for RP1F2C0.5) except for RP2F1C0.5 (which had a marginal increases) compared to LWA concrete. The lightweight nature of RPA concrete was expected due to the fact that a large volume of the concrete, around 60 to 70%, comprised lightweight material (with 100%

replacement of conventional coarse LWA). The highest reduction in fresh density, seen in RP1F2C0.5, was due to the fly ash used and the light weight of the plastic particles. Furthermore, an increase in water-cement ratio of 0.1 results in a marginal decrease in the density of fresh concrete for RPA and LWA concrete. Therefore, an increase in the w/c ratio of 0.1 had no significant effect on fresh density of either the conventional LWA or RPA concrete. It seems that the nominal decrease in fresh density of both RPA and LWA concretes was due to the reduction in quantity of the cement, which affected the overall density of concrete, as the density of cement is greater than that of aggregates.

Dry density

The results for the dry density of all types of concrete are shown in Table 6. The results show that the dry density of RPA concrete reduced (highest reduction: 9% for RP1F2C0.5), except for RP2F3C0.5, which had slightly increased as compared to LWA concrete. The light weight of the plastic and filler particles which formed RPA grains was indeed the major cause of reduction in dry density of the RPA concrete, in agreement with other studies (Kashi et al. 1999; Jansen et al. 2001; Choi et al. 2005 and Choi et al. 2009). Kashi et al. (1999) and Jansen et al. (2001) observed that the dry density of concrete made with SLA at 80 % fly ash was 15 % lower. Also, a similar trend was found by Choi et al. (2005) and Choi et al. (2009), who observed that the dry density of concrete made with WPLA at 75 % replacement was reduced by 31 %. Additionally, the increase in water-cement ratio of 0.1 did not have a significant effect on the dry density of concrete produced using RPA (i.e. RP1F1A, RP1F2A and RP1F3A concretes – see Table 6).

Compressive strength

The results for the compressive strength of all types of RPA concrete and LWA concrete at the age of 7, 14 and 28 days, with a water to cement ratio of 0.5, are shown in Figure7. The compressive strength of all concrete mixtures was observed to increase between the ages of 7 and 28 days, as expected. The percentage increase in compressive strength from 7 to 14 days was observed to be 16%, 18% and 16% for LWA, RP2F3A and RP2F1A concrete mixtures respectively. Similarly, an increase of 19%, 13% and 5% in compressive strength from 14 to 28 days was observed for LWA, RP2F3A and RP2F1A concrete respectively. The percentage difference between the maximum (RP1F3C) and minimum (RP2F2C) compressive strengths attained at 7 days among all RPA concretes was 18%. Meanwhile, the percentage difference between the maximum (RP2F3C) and minimum (RP1F2C) compressive strengths at 14 and 28 days among all RPA concretes was 12% and 22%, respectively. At 28 days, the smallest reduction in compressive strength was observed in RP2F3A concrete, which was 40% less strong than conventional LWA concrete. By contrast, the maximum reduction in compressive strength was seen in RP1F2A concrete, and was 53% as compared to conventional LWA concrete. In addition, this result suggests that variation in compressive strength percentages for RPA concrete with different proportions of filler was less prominent compared to LWA concrete. The results also suggest that RP1F3C0.5 and RP2F3C0.5 meet the strength requirements of ASTM C330-04, as they had a compressive strength which was higher than 17 MPa. Hence, these two types of concrete might be suitable for structural use.

Based on all of the above parameters, the concrete made with RPA containing the quarry fines filler had the least reduction in compressive strength, because these aggregate particles possessed an angular shape and a rough surface texture as compared to the other RPA aggregates. As a result, good bond and interlocking is expected between this type of aggregate and the cement matrix. Furthermore, generally the reduction in compressive strength for RPA concrete was due to a weak bond between the cement mortars and the recycled plastic aggregate particles, and the hydrophobic nature of plastic. Other researchers who have used manufactured plastic-based aggregate in concrete also noted significant reduction in strength as compared to natural/conventional lightweight aggregate concrete (Kashi et al. 1999; Jansen et al. 2001; Choi et al. 2005; and Choi et al 2009). Choi et al. (2005) and Choi et al. (2009) observed that using WPLA in concrete at 75 % replacement reduces strength significantly, by 33 %. A similar observation was reported by Kashi et al. (1999) and Jansen et al. (2001), who argued that concrete made with SLA at 80 % fly ash was a significant 43% lower than control concrete.

At 28 days, compression strength for concrete containing RPA with water-cement ratios of 0.5 and 0.6 is shown in Figure 8. A general trend observed was that compressive strength was inversely proportional to the water-cement ratio. On a 0.1 increase in water to cement ratio, the compressive strength of concrete made with RPA with fillers of red sand, fly ash, quarry fines and LWA concrete was decreased by 17%, 6%, 16% and 21%, respectively. The highest compressive strength among all RPA concrete was achieved by RP1F3C, with 17.58 MPa (at w/c ratio of 0.5) and the lowest by RP1F1C at 12.72 MPa (at a w/c ratio of 0.6).

Flexural strength

The results for flexural strength of all types of RPA concrete and conventional LWA concrete at the age of 7, 14 and 28 days with a w/c ratio of 0.5 are shown in Figure 9. The flexural strength of all concretes was observed to increase with age, as expected. An increase of 8% and 16% in flexural strength from 7 to 14 days was observed for RP2F1A and LWA concrete respectively. Similarly, an increase of 8% and 10% in flexural strength from 14 to

28 days was observed for RP2F1A and LWA concrete respectively. Additionally, among all RPA concretes, the percentage difference between the maximum (RP2F1C) and minimum (RP2F2C) flexural strength attained at 7 days was 14%. In comparison, the percentage difference between the maximum (RP2F1C) and minimum (RP1F2C) flexural strength at 14 and 28 days among all RPA concretes was 9% and 4% respectively. This reveals that the percentage difference in flexural strength across all RPA concrete is less prominent compared with that for compressive strength at the same age. At 28 days, the minimum reduction in flexural strength was observed in RP2F1A concrete, which was 27% less strong than conventional LWA concrete. Meanwhile, the maximum reduction in flexural strength was seen in RP1F2A concrete, at about 31% as compared to conventional LWA concrete. The flexural strength test has not been conducted previously by those researchers who used manufactured plastic based aggregate in concrete. Therefore, a comparison with previous researchers who replaced recycled plastic with aggregate was adopted. For example, Saikia and de Brito (2014), Rahmani et al. (2013), Ismail and Hashmi (2008) and Yazoghli Marzouk et al. (2007) pointed out a reduction in flexural strength due to incorporating recycled plastic as aggregate instead of conventional aggregate. Saikia and de Brito (2014) reported that flexural strength was significantly reduced by 50.5 %, 37 % and 16 % for concrete containing PC, PF and PP respectively as PET replacement levels increased from 0 % to 15%. Similarly, Rahmani et al. (2013) argue that replacing fine aggregate in concrete with PET at 15 % reduces flexural strength by 14.7 %. In a similar way, Yazoghli Marzouk et al. (2007) pointed out that the reduction in flexural strength was 88 % due to replacing sand with PET at 100 % replacement. Also, a 33 % reduction in flexural strength was demonstrated by Ismail and Hashmi (2008), who used waste plastic in concrete at 20 % replacement. The reduction in the flexural strength of RPA concrete was due to a decrease in the amount of rigid natural aggregate, which was replaced by RPA. In addition, the strength

of the cement/RPA relies essentially on surface roughness (physical interlocking), whereas with a natural aggregate, a chemical bond is formed at this interface.

The effect of water-cement ratios of 0.5 and 0.6 on the flexural strengths of concrete containing RPA and LWA is shown in Figure 10. The general trend showed that flexural strength was inversely proportional to the water-cement ratio. The flexural strength of LWA and the RPA concrete produced using fillers of red sand, fly ash, and quarry fines was decreased by 8%, 18%, 17% and 15% respectively at 0.1% increase in water-cement ratio. The highest flexural strength among all RPA concrete was achieved by RP1F3C, at about 3.72MPa (at a w/c ratio of 0.5) and the lowest by RP1F1C at 2.99MPa (at a w/c ratio of 0.6).

Microstructure investigation

A detailed analysis of the microstructure of concrete mixture samples made with RPA and LWA was performed using SEM imaging, as shown in Figure 11. In the case of RPA concrete, it is clear from the SEM image that RPA concrete made with quarry fines is more strongly bonded to the concrete cementious matrix than the RPA concrete made with fly ash. Also, the mode of failure between the matrix and RPA made with fly ash shows a wider space than that given between the cement matrix and RPA made with quarry fines. This was attributed to the higher roughness of the aggregate made with quarry fines, due to its high degree of angularity in contrast to that with fly ash particles, which have a smoothness of surface texture and a sub-spherical shape. A similar observation was made by Yazoghli Marzouk et al. (2007) as they linked the improvement in mechanical properties with improvement in bonding between aggregate and cement matrix.

It is worth noting that quarry fines particles' median size is three times larger than that of fly ash particles, which can be taken also as another justification for the weak bonding with this type of aggregate. Moreover, the loose particles of fly ash in the RPA matrix prevent good bonding, as stated earlier and shown in Figure 6. This explains the increase in the strength of RPA concrete made with quarry fines compared to the lower strength achieved by RPA concrete made with fly ash. However, concrete made with conventional LWA shows a tight mode of failure as compared to that in RPA concrete made with quarry fines. This observation shows that the concrete with LWA is more strongly bonded to the cement matrix than the RPA with the cement matrix.

Mechanism of failure

Concrete made using conventional lightweight aggregate behaved as expected at failure under flexural loading, whereas the use of RPA in concrete resulted in a more complex response as there is greater difference in stiffness between the aggregate and the matrix, compared to conventional aggregate. The former can be seen in Figure 12(a), where a brittle failure was observed, while with the latter being more flowable, thus, under loading, there is stress transfer from the aggregate to the matrix. Since no significant boundary failure was observed between aggregate and matrix, this concrete deforms in a plastic manner with no through-sample cracking until significant deformation has taken place. This behaviour can be seen in Figure 12(b, c and d). This behaviour is similar to that observed by Hannawi et al. (2010), who report that mode of failure for concrete containing PET plastic aggregate is more ductile.

Furthermore, under compression loading, two mechanisms of failure were observed during the course of this study, as follows:

1-The mode of failure in conventional lightweight concrete is characterised by crack propagation through the aggregate itself, leading to single major cracks, as shown in Figure 13(a).

2- On the other hand, due to the plastic nature within the matrix of the RPA, the mode of failure becomes different. It is found that stress transfer leads to deformation in the aggregate, instead of crushing or cracks through the aggregate, as shown in Figure 13(b). This was in agreement with Saikia and Brito (2014) and Yazoghli et al. (2007), who found that ‘‘crack propagation interval’’ was prolonged due to the presence of recycled plastic particles.

Cost effective analysis

The cost of manufacturing of synthetic aggregate is associated preliminary with the cost of manufacturing process and raw material. The manufacturing process of RPA and Lytag aggregate or other manufactured lightweight aggregates are similar as both require heating and cooling mechanism. The heating process for manufacturing RPA require less temperature and additional compression as compared to lightweight aggregate such as Lytag which requires high heating temperature of 1100°C (LYTAG 2016). Therefore, the additional compression need in case of producing RPA compensate the high temperature needed for production of Lytag or other type of manufactured lightweight aggregate. So the cost evaluation depends on the raw material cost required for production RPA and Lytag aggregate only. The raw material used for manufacturing Lytag or other type of manufactured lightweight aggregate for instance, slag, clay and shale cost $12 to $ 13 per ton (Kashi et al. 1999) and fly ash $12-15 per ton (Bedick 1995). For RPA production, the local cost of raw materials used for manufacturing RPA such as LLDPE, dune sand and fly ash are $ 853/ton, $0-5/ton and $ 160-170/ton respectively. However, the international cost for same materials are $1322/ton, $7.70/ton and $12-15/ton respectively (Block 2016; USGS 2015; Bedick 1995). The calculation was made based on the prices of the locally collected materials. Therefore, for example the cost for RPA produced using local LLDPE and dune sand are $427.75 /ton and $257.65/ton at (50/50 and 30/70) of LLDPE to dune sand respectively using the below equation (Kashi et al. 1999).In the same way, the cost of RPA produced using LLDPE and fly ash are \$509/ton and \$371.4/ton at the same proportions levels.

Material Costs (\$/ton) = % of plastic × (LLDPE cost) + % of filler × (filler cost) (Eq.1) (Kashi et al. 1999)

Also, the calculated cost of RPA would also be compensated taken into consideration the cost of landfilling required for dumping LLDPE and fly ash. The landfill cost of LLDPE is \$49 per ton (EPA 2015) and \$50/ton for fly ash (Brickhead 1995 and Bedick 1995) while there is no landfill cost for dune sand. Therefore, the below expression (Eq.2) was used to calculate the material cost after taken landfill cost into consideration (EPA 1996; cited by Kashi et al. 1999).

Material Costs (\$/ton) = % of plastic × (LLDPE cost-x_1) + % of filler × (filler cost-x_2) (Eq.2) (EPA 1996)

(Where x_1 is the disposal cost of LLDPE and x_2 is the disposal cost of filler, both in \$/ton)

As a result, the cost of RPA produced using LLDPE and dune sand using (Eq.2) was reduced to \$403.25/ton and \$242.95/ton respectively at (50/50 and 30/70) of LLDPE to filler respectively. Similarly, the cost of RPA produced using LLDPE and fly ash was also reduced to \$459.5/ton and \$321.7/ton respectively at the same proportions levels. Although, the RPA produced at (30/70) of LLDPE to dune sand shows the most cost effective amongst the RPA produced, still the cost of materials used to produce RPA is not cost effective due to low cost of dumping of plastic and fillers and high price of recycled plastic waste. However, the cost will reduce if stricter regulations are implemented which will ultimately increase the disposal cost and taxes fixed on natural aggregate mining. Also the materials cost of RPA production will be more cost effective if the price of recycled plastic is reduced by taking plastic waste from the household straightway or use it directly without any further treatments. At length, the production of RPA does not consider the energy recovered and the environmental benefits associated with reduction in plastic and granular waste. For example, recovering 3 million tons of plastic waste would reduce the CO_2 emissions by 3.8 million tons (EPA 2015). Furthermore, the cost effective study does not consider the fact that this type of aggregate (RPA) has some unique properties associated with high ductility due to the presence of the plastic in their matrix which will enhance the demand in market for particular sector.

It is worth also noting that whilst RPA is weaker than convention lightweight aggregate (LWA), it has a number of benefits, such as reduced unit weight, and could have applications in backfilling trenches, pavements or in non-structural elements where high strength is not required, as described by Alobaidi et al. (2000) and Ghataora et al. (2000), along with a range of other potential applications. Due to the reduction in weight, there will be potential cost savings in terms of cost and environmental benefit: the latter due to reduced haulage and utilisation of both plastic and previously waste granular materials.

Conclusions

Overall, RPA aggregate exhibits potential applications for use as a replacement for conventional LWA, as this innovative aggregate is lighter than LWA. Thus, the technology developed for manufacturing this aggregate, as well as the manufactured aggregate itself, has the potential to be exported outside the Gulf region to other countries which are deficient in natural, lightweight construction materials. Conclusions can be drawn from this study as elaborated below:

- Novel synthetic recycled plastic aggregate (RPA) was successfully manufactured using LLDPE and different types of fillers (at 50/50 and 30/70 LLDPE/filler).

- The novel RPA (i.e. RP1F2A, RP1F3A and RP2F2A) has satisfying ASTM C330-04 standard limits, whereas, RP1F1A, RP2F1A and LWA were deviated from the minimum permissible limits by 32 %, 26 % and 39 % % respectively. Also RPAs demonstrate lower unit weight and water absorption compared to LWA.
- The crushability of LWA is pronounced, while RPA is not crushable due to the plastic nature of its matrix.
- RPA can be used in concrete as a total replacement for conventional LWA.
- The reduction of compressive strength due to RPA incorporation was between 40 % and 53 %. Similarly, the reduction for flexural strength was between 27 % and 21 % compared to the LWA concrete.
- Compared with LWA concrete, the reduction in the flexural strength of the RPA concrete is less noticeable than the reduction in compressive strength because of the elastic and ductile behaviour of the plastic in the RPA particles. The RPA concrete can thus be used for structures where concrete with ductile behaviour is required instead of LWA concrete.
- Only two types of RPA concrete, namely RP1F3C0.5 and RP2F3C0.5, complied with the compressive strength requirements of ASTMC 330-04. Hence, it can be used for applications where low strength is accepted, such as pavements, paths and backfill of utility trenches.
- The mechanisms of failure in conventional lightweight concrete are characterized by crack propagation through the aggregate itself, whereas in RPA concrete, stress transfer leads to deformation in the aggregate instead of crushing or cracking through the aggregate.

- The RPA produced at (30/70) of LLDPE to dune sand shows the most cost effective amongst the RPA produced. However, it still costly ineffective due to low landfill and high cost of recycled plastic waste.
- The cost of RPA will reduce if stricter taxes regulations are implemented and if the plastic waste was taken from the household straightway or use it directly without any further treatments.
- Recovering plastic waste would reduce the CO_2emissions by 3.8 million tons.

Acknowledgement

The authors are grateful to King Saud University (KSU) and King Abdulaziz City for Science and Technology for sponsoring and funding this research project and to the University of Birmingham for the academic and supervision assistance. Also, the authors would like to thank SABIC for supporting this research. The authors also extend their appreciations to the CoE-CRT Center of Excellence and the laboratory staff of KSU for their full assistance during laboratory work.

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