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Novel lightweight concrete containing manufactured plastic aggregate

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HIGHLIGHTS

- Innovative concrete was produced using novel manufactured plastic aggregate.
- The effect of replacing natural aggregate with manufactured aggregate was examined.
- The mechanical properties of concrete decreased with increasing replacement level.
- The ductility of concrete increased with increasing replacement level.
- Models were proposed to predict the mechanical properties of the novel concrete.

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ABSTRACT

Plastic waste and its low recycling rate make a significant contribution towards the pollution of the environment. It is therefore essential that plastic waste is utilised in different applications, such as aggregates in concrete. In this paper, an investigation of a manufactured plastic aggregate as a replacement for volcanic lightweight aggregate and Lytag aggregate in concrete is presented. The influence of replacement level on the fresh, hardened and microstructure properties of concrete was investigated. The slump, compressive strength, flexural strength, splitting tensile strength and elastic modulus decreased with the increase in replacement level. Neither the fresh density nor the hardened density was significantly affected by replacement level. The Lytag and conventional lightweight concrete mixes had a brittle failure; whereas the concrete mixes incorporating the manufactured plastic aggregate had a ductile post-peak behaviour. The results suggest that the concrete mix containing the manufactured plastic aggregate at a replacement level of 25% can be used in structural and non-structural applications requiring moderate strength and ductility. Predictive models were proposed and demonstrated to be in good agreement with the experimental results for the mechanical properties of the concrete mixes incorporating the manufactured plastic aggregate.

1. Introduction

The use of plastic is consistently growing because of its versatility. The total plastic produced worldwide in 2014 was estimated at 313 million tonnes (Mt) [1]; in 2015 it increased to 322 Mt, which is about 3% rise in two years [2]. According to the Plastic Association, the European consumption of plastic in 2014 was 59 Mt, with almost half of this amount (i.e. 25.8 Mt) being disposed of as waste [2]. Unfortunately, the recycling rate is not encouraging, since only 29.7% of the plastic waste was recycled in Europe in 2014 and only 8.8% in the USA in 2012 [2,3].

The bulk quantity of waste plastic is usually sent to landfill or dumped into the oceans, which are the terminus in the lifecycle of plastic, causing polluting effects over long periods of time. For instance, it has been reported that around 28.95 Mt of plastic waste

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Abbreviations: CA, coarse aggregate; E_c, modulus of elasticity; FA, fine aggregate; ITZ, interfacial transition zone; LAC, concrete made using Lytag aggregate; LWA, conventional volcanic lightweight aggregate; LWC, concrete made using conventional lightweight aggregate (LWA); LYA, Lytag aggregate; RP2F1A, recycled plastic aggregate made using 30% LLDPE and 70% red or dune sand; RP2F1C, concrete made using recycled plastic aggregate (RP2F1A); RP2F1C25, the concrete mix containing RP2F1A at a replacement level of 25%; RP2F1C50, the concrete mix containing RP2F1A at a replacement level of 50%; RP2F1C75, the concrete mix containing RP2F1A at a replacement level of 75%; RP2F1C100, the concrete mix containing RP2F1A at a replacement level of 100%; RPAs, recycled plastic aggregates; SLA, synthetic lightweight aggregate; W/C, water to cement ratio; WPLA, waste PET lightweight aggregate; f_c, cylinder compressive strength; f_r, flexural strength; f_t, splitting tensile strength; γ_w, dry density.

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was disposed of in the USA in 2012 [2,3]. Moreover, Jambeck et al. [4] reported that every year, from 4.8 to 12.7 million metric tonnes of plastic waste are disposed of in the oceans. Alternatively, plastic waste is incinerated; however, this generates a significant amount of carbon and other toxic emissions, as well as the generation of residue which also presents toxicity issues [5].

For these reasons, the possibility of using plastic waste in different industries, such as the construction sector was explored. One of the potential applications is implementing plastic as replacement for aggregates in concrete, since the consumption of aggregates reached 48.3 billion metric tonnes in 2015 [6]. Several studies [7–26] were conducted on the effect of replacing coarse (CA) and/or fine aggregate (FA) in concrete with plastic. However, few studies have reported on the influence of manufactured plastic aggregate on the performance of concrete, when it is used as a replacement for aggregate [27–34].

The use of plastic to manufacture plastic aggregate has the potential to mitigate the aforementioned problems and reduce the rapid consumption of non-renewable materials such as natural aggregate. Additionally, it could overcome the drawbacks associated with existing lightweight concrete made from either natural or manufactured lightweight aggregates. For example, concrete containing natural lightweight aggregate (i.e. pumice or scoria) has high mining and hauling costs, excessive drying shrinkage and high water absorption. In the same context, incorporating a manufactured aggregate, such as Lytag, in concrete can adversely affect the durability performance due to its high permeability; along with consuming high levels of energy, supplementary materials and chemical additives during its manufacture [27–28].

The main findings of the research studies [8,10,21–22,24] conducted on concrete containing shredded or plastic aggregate particles indicate that the concrete workability, density and mechanical properties; such as compressive strength, splitting tensile strength, flexural strength and modulus of elasticity; significantly decrease with the increase in plastic content. For example, the density of concrete and cement mortar was reduced by 7 to 50% due to the increase in the ratio of plastic particles from 20 to 100% [7,9,16,18,20,22]. Other researchers [11,19] observed a marginal decrease in density, varying from 6 to 10%, at high replacement levels (from 75 to 100%) of CA or FA with plastic. Furthermore, studies [8,9,11,18,20,22,25] reported a significant reduction, ranging from 34 to 70%, in the 28-day concrete compressive strength when 20 to 100% of the conventional FA was substituted directly with plastic. Similarly, replacing 30 to 80% of the conventional CA directly with plastic resulted in a substantial reduction (ranging from 65 to 78%) in the 28-day concrete compressive strength [14,16–17,26].

Other studies [27–34] have showed a similar decreasing trend in the mechanical properties of concrete with an increase in synthetic lightweight aggregate content; while workability increased in some instances and in others it is decreased. For instance, Choi et al. [27,28] reported that the slump of concrete made with waste PET lightweight aggregate (WPLA), at a 75% replacement level of FA, was 46% higher compared to conventional concrete. This increase was attributed to the spherical shape and smooth surface texture of the WPLA particles. Conversely, a reduction in slump (ranging from 7 to 28%) was also observed by other researchers [30,31,33] when lightweight CA was fully replaced with synthetic lightweight aggregate (SLA). However, the plastic-based aggregates developed in these studies [27–34] were of the same shape and size. Additionally, these aggregates were either a composite made from plastic and fly ash, or plastic coated with either river sand or granulated blast furnace slag (GBFS). Moreover, the extrusion process used for the production of these aggregates restricted the scope of their practical utilization.

The extant literature suggests that widely available fillers (e.g. red sand and quarry fines) need to be utilized for the manufacture of well graded plastic-based aggregates. Recently, Alqahtani et al. [34,35] manufactured recycled plastic aggregates (RPAs) using different types of plastic and fillers by means of a novel technique (compression moulding press). Tests carried out on concrete samples showed that slump, fresh density and 28-day compressive strength results ranging from 40 to 220 mm, 1827 to 2055 kg/m^3 and 14 to 18 MPa, respectively, were achieved with the total replacement of CA in concrete.

The novel contribution of the present study is to implement one of the previously manufactured RPAs (i.e. RP2F1A) [34,35] as a replacement for volcanic lightweight coarse aggregate (LWA). The effect of various replacement levels (i.e. 25, 50, 75 and 100%), on a volumetric basis, on the fresh, hardened and microstructure properties was investigated. Moreover, the influence of fully replacing Lytag aggregate (LYA) with RP2F1A on the same properties was examined. Furthermore, predictive models were proposed for the mechanical properties of the concrete mixes containing RP2F1A.

2. Materials and methods

2.1. Materials

Portland cement from a local manufacturer, with a specific gravity of 3.15, was used throughout this study; which satisfied the requirements of ASTM C150/C150M. Various types of coarse aggregates; which included RP2F1A, LWA and LYA (see Fig. 1); were used together with normal-weight fine aggregate for the preparation of concrete mixes. In this study, LWA was the locally available, naturally occurring volcanic lightweight aggregate. The LYA, a commercially available lightweight aggregate, was supplied by Lytag Limited (manufacturer of LYA in the UK). The RP2F1A, which is the key material in this study, was manufactured by the authors by mixing recycled plastic (LLDPE) and red dune sand filler at proportions of 30 and 70%, respectively, to form a homogeneous mix [34,35]. This was followed by compressing and heating the mix using a compression moulding press technique to turn it into solid sheets or slabs, which were then cooled and finally crushed to form the aggregate. The LWA and LYA were used for the preparation of the control mixes; whereas the RP2F1A was used for investigating the effect of replacement level on concrete performance.

The particle shape and surface texture of RP2F1A, LWA and LYA were qualitatively examined using an optical microscope. The RP2F1A, LWA and LYA had subangular, angular and rounded particle shapes, respectively; while their textures were partially rough (fibrous), porous and smooth, respectively.

The physical properties of the aggregates are listed in Table 1. The specific gravity and absorption tests for the coarse aggregates were performed according to ASTM C127 [36]; while unit weight and void content were measured in accordance to ASTM C330/C330M [37].

As shown in Table 1, the unit weight of RP2F1A, LWA and LYA was 750, 697 and 889 kg/m^3 respectively; whereas water absorption was 2.75, 18.6 and 16.82%, respectively. These results indicate that the unit weights are comparable; while the water absorption of RP2F1A was 85 and 84% lesser compared to those of LWA and LYA, respectively. In the case of the normal-weight fine aggregate, the unit weight, specific gravity and water absorption were measured based on ASTM C29/C29M [38] and ASTM C128 [39]. The test results are also presented in Table 1.

The particle size distribution curves for RP2F1A and LWA were obtained in line with ASTM C330/C330M [37] as shown in Fig. 2. It is worth noting that the grading of LYA was prepared in the lab to match that of LWA because the former aggregate was supplied in single grades by the manufacturer. The fine aggregate used was a combination of 65% red sand and 35% crushed sand (see Table 1) in order to satisfy the requirements of ASTM C136/C136M [40] as shown in Fig. 3.

2.2. Mix proportions

A total of six mixes were considered in this study. The reference mix (LWC) was designed using LWA according to ACI 211.2 [41] to give a minimum slump of 100 mm and a minimum compressive strength of 30 MPa at 28 days for non-air entrained concrete. For comparison purposes, a second mix (LAC) was designed using LYA. The remaining four mixes included RP2F1A as replacement for LWA on a volumetric basis at 25, 50, 75 and 100% replacement levels.

The concrete mixes containing LYA and RP2F1A were designed relative to LWC by keeping the amount of cement and free water constant. For a given mix, the quantities of LWA, RP2F1A or LYA were calculated, as explained below, using the replacement level; unit weight of LWA, RP2F1A or LYA; and the quantity of LWA used in the reference mix (i.e. LWC).