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# Experimental study to investigate the engineering and durability performance of concrete using synthetic aggregates

Fahad K. Alqahtani [a,*], Gurmel Ghataora [b], Samir Dirar [b], M. Iqbal Khan [a], Idrees Zafar [c]

[a] Department of Civil Engineering, King Saud University, P. O. Box 800, Riyadh 11421, Saudi Arabia
[b] Department of Civil Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom
[c] Department of Civil Engineering, Al Imam Mohammad Ibn Saud University, P. O. Box 5701, Riyadh 11432, Saudi Arabia

## HIGHLIGHTS

- Lightweight concrete comprising synthetic aggregate was produced.
- Engineering and durability properties of produced concrete were examined.
- Durability related properties of synthetic aggregate concrete were improved.
- Reduction in brittleness of concrete containing synthetic aggregate was observed.
- Predication models were proposed for synthetic aggregate concrete.

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## ABSTRACT

Global plastic production is increasing significantly each year; however, the recycled percentage is still relatively low, which results in an on-going increase in the amount of waste plastic being stockpiled. There have been attempts to utilize waste plastic in different sectors to reduce its environmental impact, including its utilization as a replacement for aggregate in concrete. A novel synthetic aggregate has been developed based on the utilization of waste plastic. Its influence on the fresh, hard and durability properties of concrete when used as a replacement for either natural pumice lightweight coarse aggregate or Lytag aggregate were examined. The results indicated that the new synthetic aggregate fulfilled the strength requirements specified in ASTM C330/C330M-14 at 25% replacement level and provided both high abrasion resistance and post peak failure deformation. Furthermore, it was also noticed that using this aggregate in concrete exhibited low water absorption and chloride penetration as compared to control mixes. However, drying shrinkage increased with an increase in the replacement levels, but still providing similar values to that of normal weight concrete. It is evident from the results that the new synthetic aggregate has the potential to be utilised as a durable structural lightweight aggregate.


## 1. Introduction

Growth of population, increasing urbanization and rising standards of living have contributed to an increase in the quantity of plastic wastes generated through different activities. The growth of the plastic industry has been massive throughout the world, from around 5 million tonnes (Mt) in the 1950 s to approximately 322 Mt in 2015 [1,2]. In the USA, around 32 Mt of plastic waste was generated in 2012, which accounts for 12.7% of the total municipal solid waste [3]. However, the recycling rate is still not encouraging as compared to the quantity of plastic waste produced each year. In the USA, plastic recycling started in 1980, with a recycling rate of 0.3%, which despite technological advances and a more aware

*Abbreviations:* PA, Pumice lightweight aggregate; CM1, Control concrete made using pumice lightweight aggregate; LA, Lytag aggregate; CM2, Control concrete made with Lytag aggregate; SA, Synthetic aggregate; SAC, Concrete made using synthetic aggregate; SAC25, Concrete containing 25% by volume of synthetic aggregate; SAC50, Concrete containing 50% by volume of synthetic aggregate; SAC75, Concrete containing 75% by volume of synthetic aggregate; SAC100, Concrete containing 100% by volume of synthetic aggregate; W/C, Water to cement ratio; CA, Normal coarse aggregate; FA, Normal fine aggregate.

* Corresponding author.
*E-mail addresses:* bfahad@ksu.edu.sa (F.K. Alqahtani), g.s.ghataora@bham.ac.uk (G. Ghataora), s.m.o.h.dirar@bham.ac.uk (S. Dirar), miqbal@ksu.edu.sa (M.I. Khan), izhussain@imamu.edu.sa (I. Zafar).

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society, in 2012 was still just 8.8% [3,4]. The remaining quantity is either burnt or disposed of into the landfills, occupying a large area of land, which poses major environmental issues. Many plastic wastes are non-biodegradable wastes that remain in the landfills for hundreds or even thousands of years before they decompose [5].

Therefore, there is tremendous scope all over the world for setting up secondary industries for recycling and using plastic wastes. In recent years, the construction industry has proved itself a successful candidate for utilizing recycled materials in concrete. Thus, one of the solutions to address this problem is to use plastic waste in concrete such as aggregate replacement, which represents 60 to 70% of the total volume of the concrete. Additionally, the increase in the percentage of plastic waste used as a replacement for aggregate will reduce the demand for the use of natural aggregates.

In recent years, many studies have been carried out to investigate the effect of using shredded plastic or plastic particles directly as a replacement for normal coarse aggregate (CA) or fine aggregate (FA) on the properties of concrete [6–14]. These studies show that the workability, density and mechanical performance of the modified concrete were reduced, while little was reported regarding its durability performance. It has been reported that abrasion resistance was improved by 37 and 33% as a replacement for total aggregate and CA directly, with polyethylene terephthalate (PET) at 7.5 and 15% replacement levels, respectively [15,9]. According to Ferreira et al., this increase was because of the higher degree of roughness or fibrous texture given by its plastic particles. The water absorption of concrete made with plastic particles or shredded plastic at various levels (i.e. varying between 15 and 50%) of replacement for normal CA or FA was increased in the range of 17–55%, as reported by other researchers [6,16,17,18]. The authors attributed this increase to the failure of the two aggregates to mix properly within the matrix of the concrete, causing higher porosity in the matrix. Similarly, it was found that replacing either CA and/or FA with plastic increased drying shrinkage, due to the lower restraint of the plastic particles against the shrinkage of the cement paste [19,20,21]. Moreover, Kou et al. indicated that the resistance of concrete to chloride ion penetration increased by 36.2% when normal FA was replaced with crushed polyvinylchloride (PVC) pipes at 45%. Similarly, Babu and Babu (2003) obtained very low permeability of concrete (i.e. charge passed varying between 400 and 700 Columbus) at different replacement levels (i.e. from 20 to 37%) of total aggregate with expanded polystyrene (EPS) [22]. In addition, in a recent using the short-term mechanical performance of concrete using the recycled plastic aggregate under elevated temperatures has been studied [23]. However, as per the author's knowledge, the durability aspect of concrete incorporating lightweight aggregate produced by plastic is limited.

In the previous works carried out by the authors of the current study, different compositions of synthetic aggregates were developed and incorporated in concrete either as a total or partial replacement for CA [24,25]. These studies indicated the superior behaviour of synthetic aggregate concrete (synthetic aggregate made using 30% LLDPE and 70% red dune sand) in terms of mechanical performance and therefore, this type of concrete was selected for carrying out further investigation to evaluate its resistance against abrasion, drying shrinkage and durability performance at different replacement ratios.

In the present experimental study the use of synthetic aggregate (i.e. SA) as a replacement for pumice lightweight coarse aggregate (PA) at various replacement levels (at 25, 50, 75 and 100%) and, as a replacement for Lytag aggregate (LA) at 100% was inspected. Accordingly, the influence of increasing the replacement percentages of either the PA or LA with SA on the hardened and durability properties of concrete at a constant W/C of 0.50 was examined. In addition, analytical correlations between compressive strength and other properties (i.e. abrasion, chloride permeability) were developed.

## 2. Development of synthetic aggregate

Various kinds of granulated recycled plastics, made originally from a liner low-density polyethylene (LLDPE) were mixed with red dune sand filler to form the synthetic aggregate. The recycled plastic of LLDPE was provided in a powder form by a local supplier after passing through treatment processes comprised of collection, cleaning, shredding, melting, pelletizing and finally grinding into a powder form.

The SA was manufactured by mixing LLDPE and dune sand at proportions of 30 and 70%, respectively, to form a homogeneous mix; followed by compressing and heating of this mix to turn it into solid sheets or a slab, then cooling and finally crushing. The production of the synthetic aggregate is described in detail elsewhere [26].

The new aggregate (SA) was used as a coarse aggregate with a nominal maximum size of 10 mm, similar to those of the PA and LA. The particle shapes of the SA were sub angular as compared to the angular and rounded shapes of PA and LA respectively (Fig. 1). The texture was partially rough (fibrous), porous and smooth for the SA, PA and LA respectively, as shown in Fig. 1. Tables 1 and 2 show an insignificant difference in the unit weight of the SA and PA or LA; whereas, water absorption of the SA was 85 and 84% lesser compared to the PA and LA, respectively.

The particle size distribution curve for SA (Fig. 2) was obtained in line with ASTM C330/C330M-14 in comparison with the PA and the lightweight aggregate grading limits [27]. The grading of the LA was prepared in the laboratory to match that of the PA because it was supplied in a range of single sizes by the manufacturer.

Scanning electron microscopy (SEM) of the SA sample was also conducted, which indicated that the red dune sand filler particles are embedded in the plastic matrix in a high concentration, as compared to the binder agent (i.e. LLDPE plastic) (Fig. 3a). This confirmed the efficiency of the mixing and preparation method for producing this aggregate. Additionally, close-up images of the sample (Fig. 3b) show that the dune sand filler particles are strongly bonded into the matrix of the plastic with a few void spaces.

## 3. Materials and methods

### 3.1. Materials

#### 3.1.1. 1Cement

Ordinary Portland cement from a local manufacturer was used which satisfied ASTM C150/C150M-2016c [28]. The main tested properties comprise specific gravity (3.15), consistency (23.5%), initial setting time (45 min) and final setting time (135 min).

#### 3.1.2. Aggregates

Fig. 1 shows the coarse aggregates i.e. PA, LA and SA, used along with normal weight fine aggregate for the preparation of the concrete mixes. In this study, the PA was the locally available natural pumice lightweight aggregate. The LA was supplied by Lytag Limited (manufacturer of Lytag in the UK), while SA was produced by the authors [26]. Table 2 shows the physical properties of the PA and LA. The specific gravity and absorption of these aggregates were tested according to ASTM C127-15 and ASTM C330/C330M-14 respectively [27,29].

As shown in Fig. 4, fine aggregate was used in a combination of red sand and crushed sand with a proportion of 65% and 35% respectively to meet the ASTM C136/C136M-14 [30]. The unit weight, specific gravity and water absorption of the fine aggregate