University of Birmingham
Research at Birmingham

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

Alqahtani, Fahad; Ghataora, Gurmel; Dirar, Samir; Khan, Mohammad Iqbal; Zafar, Idrees

DOI:
10.1016/j.conbuildmat.2018.04.018

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Alqahtani, F, Ghataora, G, Dirar, S, Khan, MI & Zafar, I 2018, 'Experimental study to investigate the engineering and durability performance of concrete using synthetic aggregates', *Construction and Building Materials*, vol. 173, pp. 350-358. https://doi.org/10.1016/j.conbuildmat.2018.04.018

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 10/04/2018

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 23. May. 2025

Experimental Study to Investigate the Engineering and Durability Performance of Concrete Using Synthetic Aggregates

Fahad K. Alqahtani[1,2*], Gurmel Ghataora[2], Samir Dirar[2], M. Iqbal Khan[1] and Idrees Zafar[3]
[1]Department of Civil Engineering, King Saud University, KSA
[2]Department of Civil Engineering, University of Birmingham, UK
[3]Department of Civil Engineering, Al Imam Mohammad Ibn Saud University, KSA

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.

Keywords: plastic waste; synthetic aggregate; lightweight concrete; abrasion; drying shrinkage; durability.

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

1.0 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 1950s 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 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. (2012), 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 to 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. (2009) 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.

2.0 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 Figure 1. Table 1 and Table 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.

PA LA SA

Figure 1: Various types of coarse aggregate used in this study: PA; LA; and SA

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.

Table 1: Physical properties of SA

Physical Property	**SA**
Dry Unit Weight (kg/m^3)	750
Absorption (%)	2.75
Type	Crushed
Particle Shape	Sub angular
Surface Texture	Partially rough/ Fibrous
Nominal Maximum Size (mm)	10

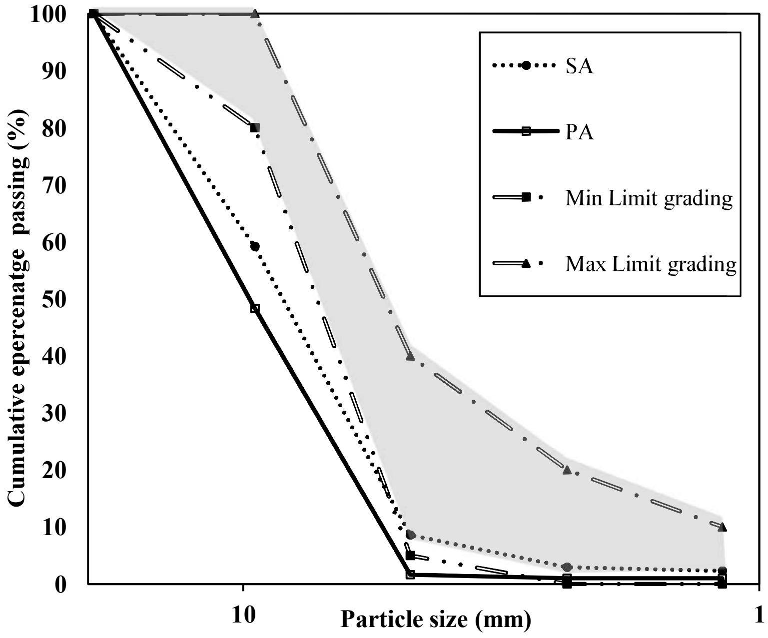
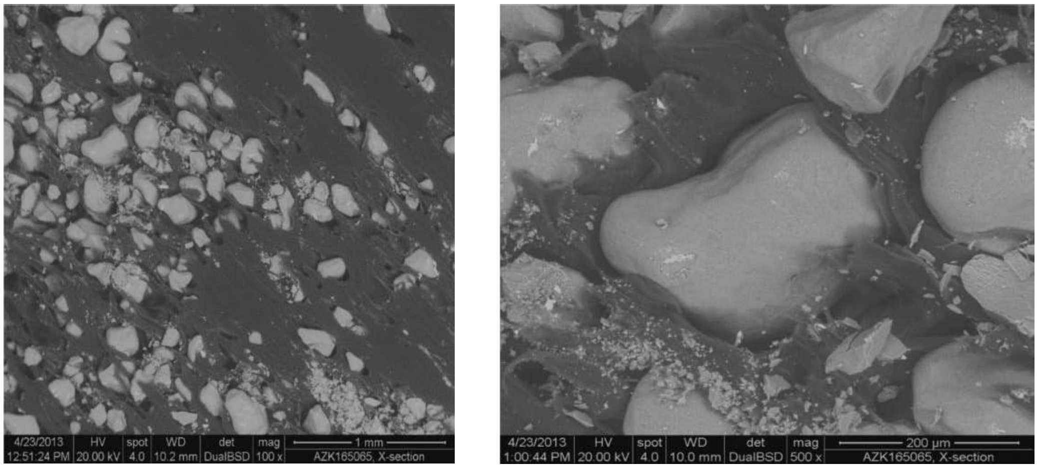


Figure 2: Particle size distribution curve for SA and PA along with grading limits for lightweight aggregate

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.



a b

Figure 3:Scanning electron microscopy of SA made with red sand (magnification: 100× (a); 500× (b))

3.0 Materials and methods

3.1 Materials

3.1.1Cement

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

Figure 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 Figure 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 were measured according to ASTM C29/C29M-16 and ASTM C128-15 respectively [31, 32]. The values of these properties are listed in Table 2.

Table 2: Physical properties of coarse and fine aggregates used in this study

Physical Property	**Coarse Aggregate**		**Fine Aggregate**	
	PA	**LA**	**Crushed sand**	**Red sand**
Dry Unit Weight (kg/m^3)	697	889	1599	1589.6
Absorption (%)	18.6	16.82	1.67	0.28
Fineness Modulus	6.5	-	3.89	1.54
Type	Uncrushed	Pelletising	Crushed	Uncrushed
Particle Shape	Angular	Rounded	-	-
Surface Texture	Porous	Smooth	-	-
Nominal Maximum Size (mm)	10	10	4.75	1.18

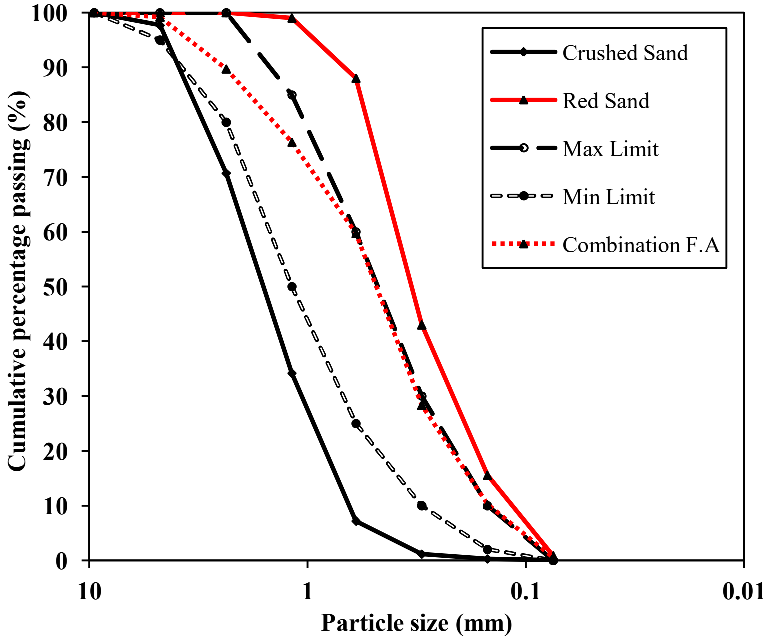


Figure 4: Particle size distribution of red sand, crushed sand and a combination of red and crushed sand

3.2 Mix proportions

In this study, six concrete mixes were designed at a constant W/C ratio of 0.50. The CM1 (as a natural lightweight control mix) was proportioned in accordance with ACI 211.2-98 [33]. For comparison purposes, another control mix (CM2) was designed using Lytag aggregate (as a manufactured lightweight control mix). CM1 and CM2 mixes were prepared using natural pumice lightweight aggregates and Lytag aggregates respectively. The remaining four mixes were casted by replacing SA for PA at 25, 50, 75 and 100% replacement levels.

The concrete mixes containing LA and SA were designed relative to reference mix (CM1) by keeping the amount of cement, W/C and free water constant to eliminate any effect, except that resulting from changing the type and replacement level of the coarse aggregate. For a given mix, the quantities of coarse aggregate of PA, LA and SA were calculated by using volume replacement method.

These mixes were prepared, cast and cured in accordance with ASTM C192/C192M-16a [34]. Table 3 illustrates the mixture proportions for the mixes per m^3. In this table, the designation "MX" refers to synthetic aggregate concrete made at X volume replacement of the PA with SA.

Table 3: Mix proportions per metre cube for different mixes

Concrete type	**W/C**	**Total water (kg/m^3)**	**Free water (Kg/m^3)**	**Cement (Kg/m^3)**	**Fine aggregate (Kg/m^3)**	**Coarse aggregate**		
						PA (Kg/m^3)	**SA (Kg/m^3)**	**LA (Kg/m^3)**
CM1	0.5	296.2	225	450	922	352	-	-
CM2		302.3			759	-	-	452
M25		282.5			918	264	95	-
M50		269.6			913	176	189	-
M75		255.6			909	88	284	-
M100		241.1			906	-	378	-

3.3 Tests conducted and methods

In this investigation, fresh concrete properties, including slump and fresh density were measured in accordance to ASTM C143/C143M-15 and ASTM C138/C138M-16, respectively [35, 36]. Concrete compressive strength tests were conducted using a 100 by 200 mm cylinder in accordance with ASTM C39/C39M-16; while, 50 by 100 mm cylinder specimens were used for splitting tensile strength tests as specified in the ASTM C496/C496M-11. The resistance of concrete against abrasion was evaluated for 200 × 200 × 50 mm specimens in line with procedures described in ASTM C944/C944M−12 [37]. Drying shrinkage of hardened concrete prisms of 75 × 75 × 285 mm was conducted in accordance to ASTM C157/C157M-08 [38]. Furthermore, the flexural deformation was measured for a single point loading prism using an INSTRON machine (model 3367), as shown in Figure 5. In this test, load was applied vertically at 0.2 mm/min and simultaneously the respective increase in the deflection was measured and recorded directly by the machine.

F

Figure 5: Failure deformation test setup using INSTRON machine

Dry density and water absorption was measured according to BS EN 12390-7:2009 and BS EN 1881-122:2011 respectively, using a 50-mm cube; whereas, chloride ion penetration was performed for concrete 50 × 100 mm cylinders in accordance with ASTM C1202-12 [39, 40]. These tests were conducted at 28 days, except for drying shrinkage readings, which were taken on a weekly basis starting from the day of demoulding, up to 182days. The results of the hardened properties were calculated as the average of three measurements.

4.0 Results and discussion

4.1 Fresh properties

Table 4 presents the slump and fresh density results of SAC, CM1 and CM2.

Table 4: Fresh properties results of RP2F1C, LWC and LAC

Concrete type	Slump (mm)	Fresh density (kg/m^3)
CM1	220	2053
CM2	245	1935
SAC25	195	2045
SAC50	189	2041
SAC75	181	2019
SAC100	170	1987

The SAC mixes had 11-23% lower slump than that of CM1, as the replacement levels of PA with SA were increased from 25 to 100%. Similarly, SAC100 had 31% lower slump than that of CM2. A similar trend of decrease in slump, in range of 7% to 16 % at 100% replacement of CA with plastic based aggregate (SLA) was reported by Jansen et al. (2001) and Slabaugh et al. (2007) [41, 42].

The high percentage of slump in the CM1 and CM2 can be ascribed to the higher amount of absorption water for LA and PA that might not be absorbed totally during the mix and to the spherical shape of the PA and LA particles. However, the observed reduction with the inclusion of the SA is related to the sub angular particles’ shape and fibrous surface textures, which increase the contact surface area between the aggregate and the paste. Thus, more paste is needed to cover this area, which would ultimately reduce the concrete’s slump.

Additionally, SACs mixes had insignificantly (less than 4%) lower fresh density than that of CM1 and CM2. This small variation between the density of SACs and control mixes can be credited to the small differences between the unit weights of their aggregates (SA, PA, LA), as given in Tables 1 and 2. Other researchers have observed a reduction in fresh density ranging from 3 to 18% when replacing CA or FA directly with plastic at different substitutions levels varying from 15 to 50% [7, 9, 11, 13, 17].

4.2 Hardened properties

4.2.1 Mechanical properties

Table 5 shows the results of 28-day dry density, compressive strength and splitting tensile strength for concrete made with SA in comparison with CM1 and CM2.

Table 5: Mechanical properties results of concrete mixes

Concrete type	Dry density (kg/m^3)	Compressive strength (MPa)	Splitting tensile strength (MPa)
CM1	1803	31.7	2.63
CM2	1744	32.6	2.37
SAC25	1799	26.9	2.28
SAC50	1872	20	2.22
SAC75	1852	19	2.01
SAC100	1786	12	1.81

Similar to the case of fresh density, there was insignificant difference (i.e. less than 4%) between the dry density of SAC mixes and that of either CM1 or CM2. This can be because of the least differences between the densities of their aggregates, as reported in section 4.1.

The 28-day compressive strength of SAC mixes lowered by 15 to 62% than that of CM1, as the replacement level increased from 25 to 100%. Similarly, replacing 100% LA with SA reduced the 28-day compressive strength by 63% as compared to the CM2. These results indicate that the SAC is less strong than CM1 and CM2. Nonetheless, the reduction observed in SAC is lesser than the values reported in the literature [9, 10, 18, 43, 44]. In these studies, reductions varied from 62 to 82% on replacing normal CA with plastic at different replacement levels (from 15 to 80%).

In addition, it was also observed that the SACs had 12 to 31% lower splitting tensile strength than that of CM1. Moreover, SAC100 had 25% lower splitting tensile strength than that of CM2. These results are in agreement with that reported elsewhere [41, 45]; where replacing

75 and 100% of CA and FA with plastic based aggregates decreased splitting tensile strength by 33 and 26%, respectively.

Generally, the reduction in mechanical properties is attributed to the poor bonding between the cement paste and the SA, which decreases the resistance of the matrix against the load and thereby increases the concentration of stress around the aggregate particles. This poor bonding results from the hydrophobic nature of SA due to the presence of plastic in its matrix [11, 13, 14].

The SAC mixes containing 25, 50 and 75% replacement levels had compressive strength results higher than the minimum requirements (17 MPa) of the ASTMC330/C330M (Table 6). Furthermore, the SAC mixes with 25 and 50% replacement levels had a splitting tensile strength higher than the minimum requirements (2.1 MPa) of the ASTMC330/C330M. However, of these mixes, only SAC25 meets the density, compressive strength and splitting tensile strength requirements given in Table 6. Thus, these results confirm the potentiality of SAC25 as a promising structural lightweight concrete mix; where both a low density and moderate strength is required.

Table 6: Lightweight concrete properties according to ASTM C330/C330M

Average 28-day density, max (kg/m^3)	Average 28-day splitting tensile strength, min (MPa)	Average 28-day compressive strength, min (MPa)
1840	2.3	28
1760	2.1	21
1680	2.1	17

4.2.2 Abrasion resistance

Figure 6 shows the results of the 28-day abrasion of SAC mixes compared with that of CM1. The CM1 had a mass loss of 1.03gm; while the mass loss of SAC mixes ranged from 0.42 to 0.75 gm.

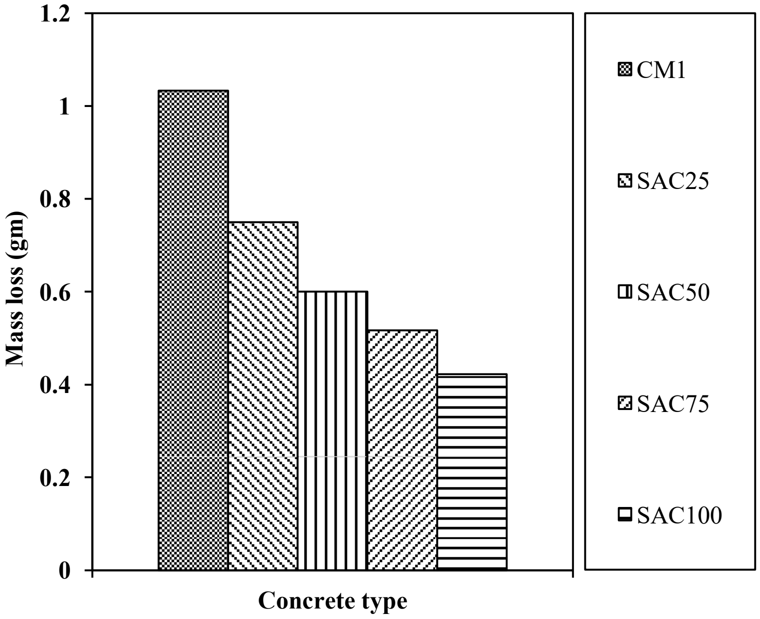


Figure 6: Results of mass loss of SACs and CM1 at 28 day

As shown in Figure 6, the reduction in abrasion of SAC mixes compared to that of CM1 ranged from 29 to 58% (0.28 to 0.61 gm) as the substitution level of PA with SA increased from 25 to 100%. These results are in agreement with the findings of Ferreira et al. (2012) and Saikia and de Brito (2014) who reported an abrasion resistance increase of 28-42% as a result of replacing 7.5-15% of CA and FA with plastic particles [9, 15] . The possible reason for the reduction in abrasion of SAC is the increase in the resistance of its aggregate particles (SA) towards abrasion due to its plasticity nature together with its fibrous surface texture [15].

The SAC mixes with 25, 50, 75 and 100% replacement levels, had abrasion results lower than that of control mix. However, of these mixes, only SAC25 mix meets the density and strength requirements (Table 6), as specified by ASTM C330/C330M-14. Thus, the results suggest that the SA could potentially be used at 25% replacement level in structural lightweight applications where high wearing resistance and mechanical performance are required, such as in pavements [46].

Additionally, the experimental results of the SAC mixes shown in Figure 7, were used to explore the correlation between the 28-day abrasion or mass loss (y) and the 28-day cylinder compressive strength (f_c). The relationship between y and f_c for SAC mixes can be expressed in Eq.1as follows.

$$y = 0.0222\, f_c + 0.1401 \qquad \text{(Eq. 1)}$$

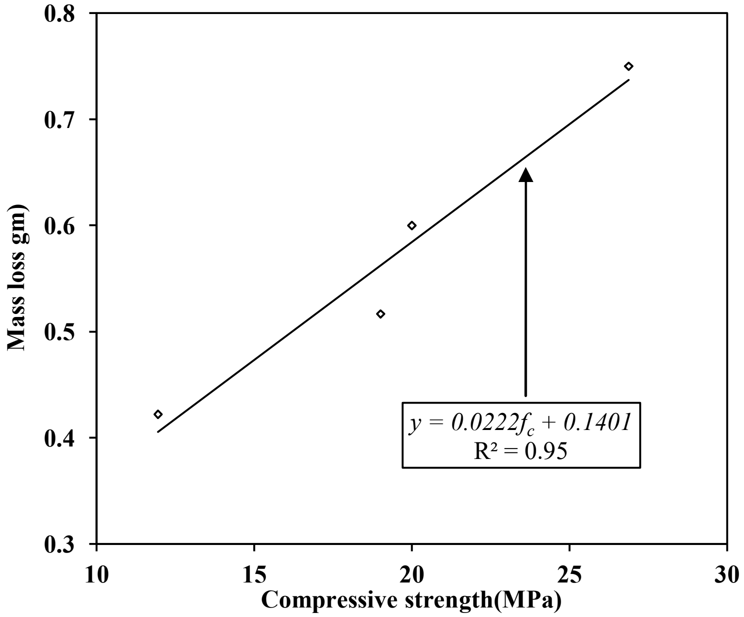


Figure 7: Correlation between mass loss and compressive strength

The relationship shows a proportional trend between compressive strength and mass loss that is unusual for normal weight concrete. However, for SAC mixes, this trend is valid because the inclusion of SA in concrete improves abrasion resistance but it decreases compressive strength, as reported in the section 4.2.1.

Equation 1 correlates well with the experimental data with a high coefficient of correlation ($R^2 = 0.95$). Additionally, Equation 1 exhibits good estimates, i.e. within ± 8.9% variation for the abrasion of SAC mixes, as shown in Table 7.

Table 7: Percentage difference in model predictions for the mass loss

Concrete type	**Percentage difference between the predicted and experimental results**
	Eq. 1
SAC25	-1.7
SAC50	-2.6
SAC75	8.9
SAC100	-3.9

4.2.3 Drying shrinkage

The results of the drying shrinkage for SAC50 and SAC100 in comparison with CM1 and CM2 are shown in Figure 8.

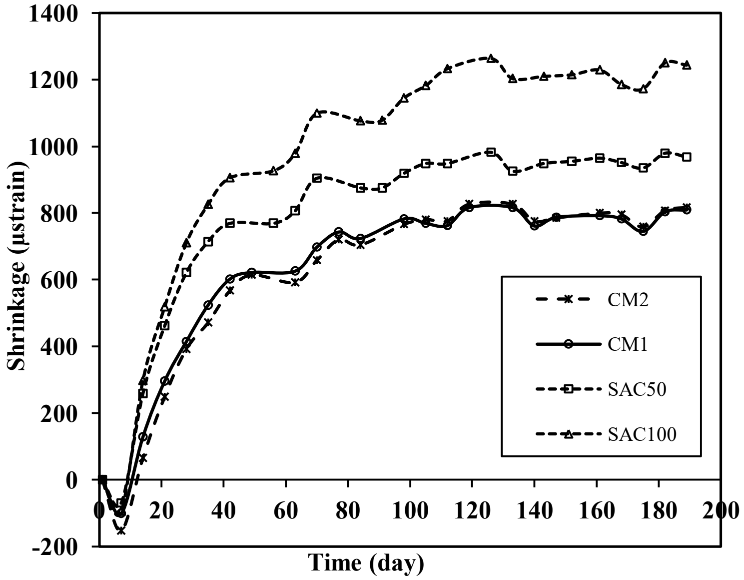


Figure 8: Results of drying shrinkage of SACs, CM1 and CM2

Figure 8 shows that the increase in the drying shrinkage of the SAC mixes compared with that of CM1 ranged from 36 to 58%, 17 to 46% and 19 to 54% at 28, 91 and 182 days of air curing respectively, as the replacement level was increased from 50 to 100%. Additionally, SAC100 had a drying shrinkage that was 75%, 49% and 52% higher than that of CM2 at 28, 91 and 182 days of air curing respectively.

The amount of drying shrinkage is controlled by water loss. However, as only the matrix loses the water, consequently the increase in drying shrinkage of SAC mixes, as compared to the control mixes is because of the weaker bond between the cement matrix and manufactured aggregates than between the matrix and reference aggregate. Therefore, during shrinkage, the movement between the cement matrix and manufactured aggregate is much easier than the reference aggregates [19]. Additionally, the increase in the drying shrinkage of the SAC mixes can also be attributed to the low water absorption of SA, which does not compensate for the water loss from the cement matrix. In contrast, the decrease in the drying shrinkage of LWC and LAC is compensated by the high absorption of PA and LA; the absorbed water released from the aggregates compensates the water loss from the cement matrix.

Nonetheless, the increase in drying shrinkage of the SAC mixes is still lower than that reported elsewhere [20, 21]; where replacing 45 and 55% of CA and both aggregates (CA, FA) with plastic particles increased the 28 and 90 day drying shrinkage by 149 and 78%, respectively. Furthermore, the drying shrinkage achieved by the SAC mixes is in agreement with that reported for normal weight concrete [47, 48]; where drying shrinkage of 800 to 1000 µstrain was observed at different drying periods (119 to 182 days). Thus, the present study results suggest that the drying shrinkage given by the SAC mixes becomes acceptable with respect to the application of these types of concrete when compared to the normal concrete performance.

4.2.4 Flexural deformation

The influence of incorporating SA as a substitution for PA on the deformation of concrete is given in Figure 9. The decrease in the maximum flexural load compared to that of PA ranged from 27-43%, as the replacement level increased from 25 to 100%. At high deformation (0.7

mm), concrete made with SA at 50, 75 and 100% replacement was able to preserve 21, 27 and 47% of their peak loads in contrast with CM1, which observed brittle failure (no post peak deformation). Therefore, the concrete made with SA yields post peak failure deformation; since it can hold the load for a longer period after failure without full splitting.

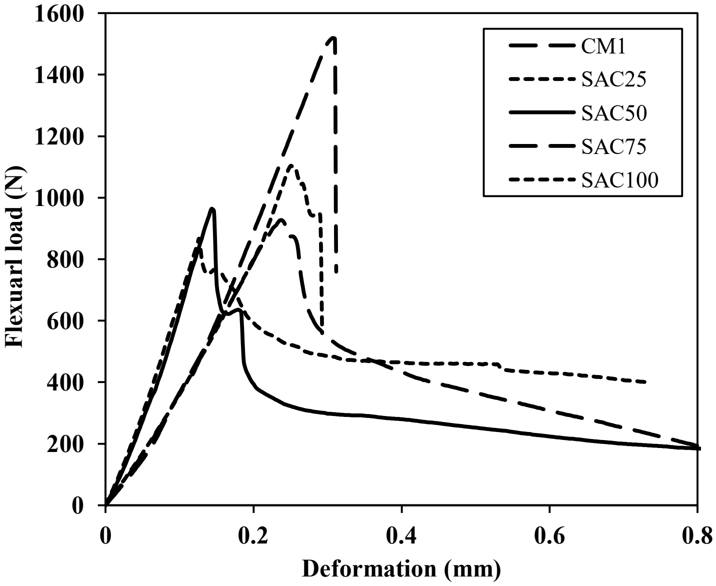


Figure 9: Results of 28-day flexural deformation of SACs and CM1

In addition, it was also noticed that the capacity of concrete to deform under load (i.e. ductile response) was proportionally increased with the increase in the replacement level. This behaviour can be linked with high deformation capacity of the plastic that exist in the SA matrix. Similar ductile behaviour by using plastic directly as a replacement for FA at various levels (from 10 to 50% replacement) was also observed in the previous studies [13, 17].

Overall, the SAC mixes with 25, 50, 75 and 100% replacement levels achieved flexural deformation results higher than that of control mix. However, of these mixes, only SAC25 mix meets the density and strength requirements given by the ASTM C330/C330M-14 (Table 6). Therefore, these results suggest that the SAC25 can be used in number of structural lightweight applications where a low density, moderate strength and high deformation are required.

4.3 Durability properties

4.3.1 Water absorption

Figure 10 shows the 28-day water absorption results for the concrete mixes considered in this study. The CM1 and CM2 had 28-day water absorption of 6.5 and 6.8%, respectively; whereas the SAC mixes, had water absorption results ranging from 5.2 to 6.4%.

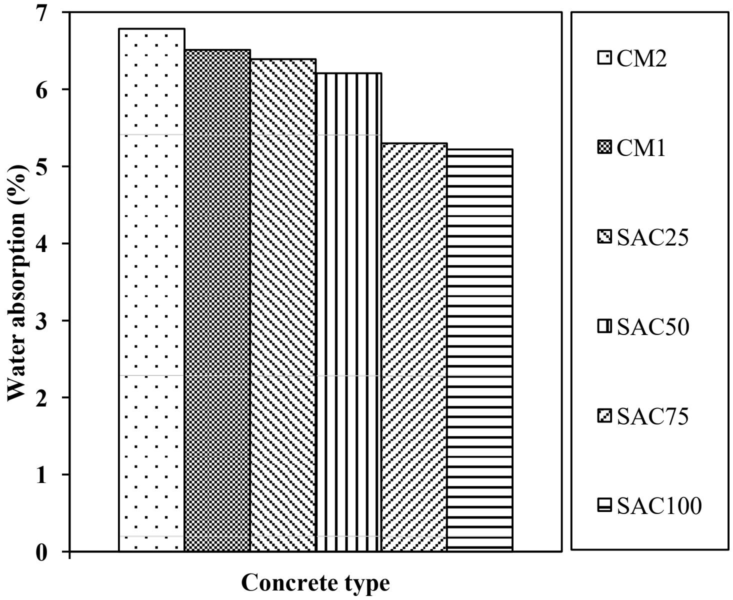


Figure 10: Results of 28-day water absorption of SACs, CM1 and CM2

The decrease in the water absorption of the SAC mixes compared with that of CM1 ranged from 5 to 20%, as the replacement level increased from 25 to 100%. Similarly, SAC100 had a 28-day water absorption 23% less than that of CM2. The decrease in the water absorption values is due to the lower water absorption of new synthetic aggregate (85%) than that of PA and LA (Tables 1 and 3). This observation is consistent with the finding of Babu et al. (2006)

who reported water absorption reduction of EPS concrete due to the non-absorbent nature of plastic particles [16].

Overall, the present study results confirm that SAC mixes made with 25, 50, 75 and 100% replacement levels had water absorption results lower than that of control mixes. However, only SAC25 mix satisfy the density and strength requirements of ASTM C330/C330M-14, as presented in Table 6. Consequently, these results further confirm the potential of SAC25 as a durable lightweight structural concrete mix.

4.3.2 Chloride permeability

Figure 11 presents the results of the chloride permeability of the SAC mixes, in comparison with that of CM1 and CM2.

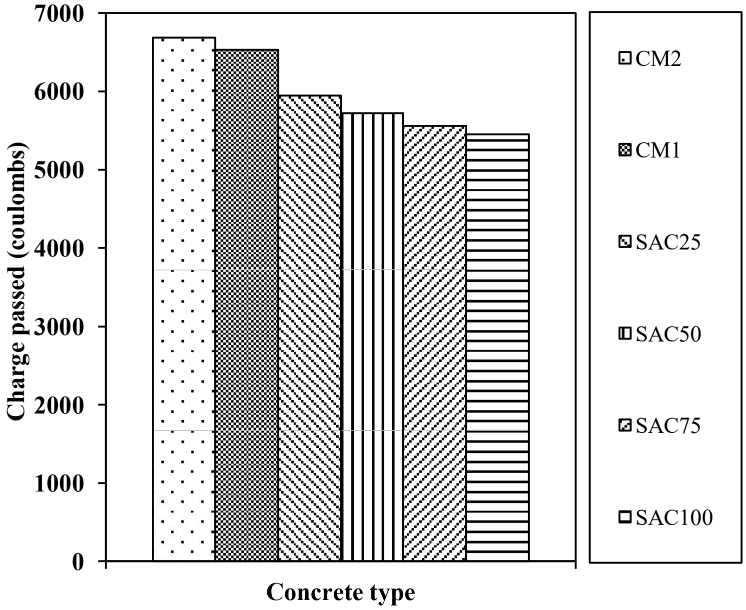


Figure 11: Results of 28-day chloride permeability of SACs, CM1 and CM2

Figure 11 shows the reduction in 28-day chloride permeability of SAC mixes compared with that of CM1 ranged from 9 to 17% as the replacement level of PA with SA increased from 25 to 100%. Additionally, SAC100 had 28-day chloride permeability 18% lesser than that of CM2. These results are in line with the previous studies of chloride permeability reductions of 43 and 36% as a result of substituting 37 and 45% of total aggregates (CA, FA) and FA with plastic particles, respectively [11, 22].

The decrease in the chloride permeability may be because of lowered ion conductivity and impervious nature (i.e. less absorption) of the plastic that exists in the SA matrix [11]. Consequently, the passage for ion transfer is disrupted and thereby, chloride ion penetration is reduced (i.e. less charge is passed). However, the high chloride permeability observed for CM1 and CM2 may be attributed to the high water absorption of its concrete and subsequent aggregate (see section 4.3.1).

Although, the SAC mixes yielded lower permeability than that of control mixes at all replacement levels, these mixes are still classified into high penetrability concrete as per the ASTM C1202-12. Nonetheless, the SAC mixes containing up to 25% replacement levels could still be used in structural lightweight applications where a low chloride level exists since it meets the density and strength requirements of ASTM C330/C330M-14.

Furthermore, in this study, the experimental results of the SAC mixes presented in Figure 12 were used to explore the correlation between the charge passed (y) and the cylinder compressive strength (f_c) at 28 days. Results of Kou et al.'s (2009) study were also used to develop a correlation for the sake of comparison [11].

The correlation between y and f_c is expressed in Eq. 2 and Eq. 3 for SAC and Kou's study respectively.

$$y = 33.8(f_c) + 5011.6 \qquad \text{(Eq. 2)}$$

$$y = 89.3(f_c) + 1952.3 \qquad \text{(Eq. 3)}$$

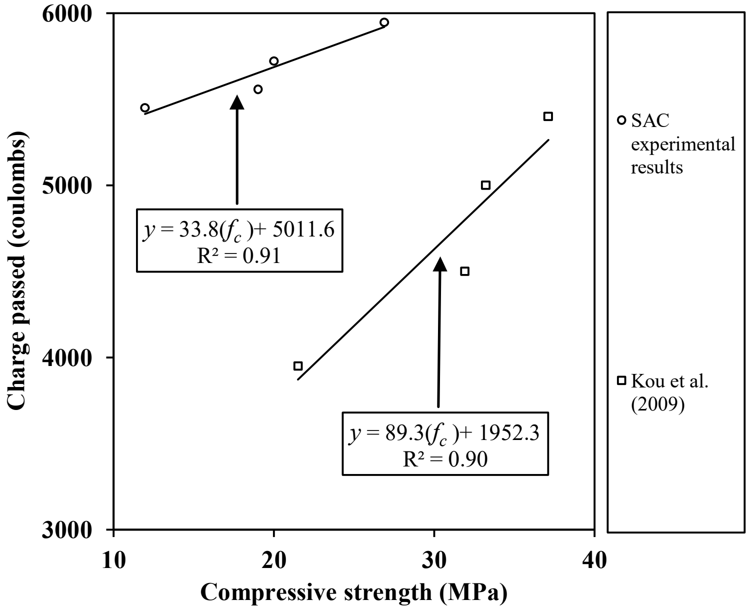


Figure 12: Correlation between 28-day chloride permeability and compressive strength

These correlations indicate that the chloride permeability had a proportional relationship with compressive strength, since both decreased as the replacement level was increased.

Table 8 presents the percentage difference between the predictions of Equations 2 to 3 and the experimental results. As shown in Table 8, Equation 2 exhibits good estimates, i.e. within ± 1.7% for the chloride permeability of the SAC mixes. On the other hand, Kou's model substantially underestimates the chloride permeability of the SAC mixes by 26.8 to 44.6%. This difference is mainly because of the dissimilarity in the experimental conditions, including all parameters of mixes.

Table 8: Percentage difference in model predictions for the chloride permeability

Concrete type	**Percentage difference between the predicted and experimental results**	
	Eq. 2	**Eq. 3**
SAC25	-0.4	-26.8
SAC50	-0.6	-34.7
SAC75	-1.7	-34.3
SAC100	-0.6	-44.6

5.0 Conclusions

In the current study, an experimental investigation was done to observe the effect of synthetic aggregates on the fresh, hardened and durability properties of lightweight concrete at different replacement levels. In addition, analytical models for the abrasion and chloride permeability of the synthetic aggregate concretes were also proposed. The main conclusions of this study are listed below.

- The synthetic aggregate concretes were found to have less consistency as compared to the control mixes. The slump of SAC mixes was lower by 11-23% as compared to the CM1, and it was 31% lower than that of CM2. Low water absorption and angular particle shapes of SA caused the decrease in the values of slump.
- The synthetic aggregate concretes showed lower mechanical performance as compared to natural lightweight aggregate concrete and Lytag aggregate concrete. The decrease in the 28-day compressive and splitting tensile strength of SAC mixes compared to that of CM1 ranged from 15 to 62% and from 12 to 31% respectively, as the replacement level was increased from 25 to 100%. Similarly, 100 % replacement of LA decreased compressive and splitting tensile strength by 63% and 25% respectively. The decrease in the mechanical properties of synthetic aggregate concrete is mainly attributed to the poor bonding between the cement paste and the synthetic aggregate.
- The synthetic aggregate concrete had shown better performance against abrasion than control mixes. However, SAC yielded a substantial increase in the drying shrinkage values as compared to control mixes. The 182-day drying shrinkage of the SAC mixes increased by 19-54%, as the replacement level of PA with SA was increased from 50 to 100%. Similarly, replacing LA totally with SA increased the 182-day drying shrinkage by 52%, as compared to the CM2. Moreover, SAC under flexural

load has displayed ductile behaviour in contrast with the brittle failure observed for CM1.

- The synthetic aggregate concretes showed high durability in terms of water absorption and chloride permeability as compared to that of natural lightweight aggregate concrete and Lytag aggregate concrete. The 28-day water absorption and chloride permeability of SAC mixes decreased by 5-20% and 9-17% respectively, with the increase in replacement level of PA with SA from 25 to 100%. Additionally, at 100% replacement of LA the reduction in water absorption and chloride permeability for SAC was 23 and 18% respectively. In addition, the analytical models for the abrasion and chloride permeability of the synthetic aggregate concretes were also proposed.
- The SAC25 could potentially be used as a durable lightweight structural mix where a low chloride level exists as it meets requirements of ASTM C330/C330M-14. However, it is suggested to carry out further detailed and long term mechanical and durability testing, including the environmental and economical evaluation, to verify the potential usage of the synthetic aggregates for civil infrastructure.

Acknowledgement

The authors are grateful to King Saud University (KSU) for academic and research assistance. The authors also extend their appreciation to the laboratory staff of KSU for their full assistance during laboratory work.

References

1- Siddique, R., Khatib, J., and Kaur, I. (2008). Use of recycled plastic in concrete: a review. Waste management, 28(10), 1835-1852.

2- PlasticsEurope, E., 2016. Plastics-the Facts 2016. An analysis of European latest plastics production, demand and waste data.

3- EPA, 2014. Municipal Solid Waste Generation, Recycling, and Disposal in the United States Detailed Tables and Figures for 2012. US Environmental Protection Agency.

4- Gu, L. and Ozbakkaloglu, T., 2016. Use of recycled plastics in concrete: A critical review. Waste Management, 51, pp.19-42.

5- Pappu, A., Saxena, M. and Asolekar, S.R., 2007. Solid wastes generation in India and their recycling potential in building materials. Building and Environment, 42(6), pp.2311-2320.

6- Albano, C., Camacho, N., Hernandez, M., Matheus, A. and Gutierrez, A., 2009. Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios. Waste Management, 29(10), pp.2707-2716.

7- Rahmani, E., Dehestani, M., Beygi, M.H.A., Allahyari, H. and Nikbin, I.M., 2013. On the mechanical properties of concrete containing waste PET particles. Construction and Building Materials, 47, pp.1302-1308.

8- Juki, M.I., Awang, M., Annas, M.M.K., Boon, K.H., Othman, N., Roslan, M.A. and Khalid, F.S., 2013. Relationship between compressive, splitting tensile and flexural strength of concrete containing granulated waste Polyethylene Terephthalate (PET) bottles as fine aggregate. In Advanced Materials Research (Vol. 795, pp. 356-359). Trans Tech Publications.

9- Saikia, N. and de Brito, J., 2014. Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. Construction and building materials, 52, pp.236-244.

10- Tang, W.C., Lo, Y. and Nadeem, A.B.I.D., 2008. Mechanical and drying shrinkage properties of structural-graded polystyrene aggregate concrete. Cement and Concrete Composites, 30(5), pp.403-409.

11- Kou, S.C., Lee, G., Poon, C.S. and Lai, W.L., 2009. Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. Waste Management, 29(2), pp.621-628.

12- Wang, R. and Meyer, C., 2012. Performance of cement mortar made with recycled high impact polystyrene. Cement and Concrete Composites, 34(9), pp.975-981.

13- Ismail, Z.Z. and Al-Hashmi, E.A., 2008. Use of waste plastic in concrete mixture as aggregate replacement. Waste Management, 28(11), pp.2041-2047.

14- Rai, B., Rushad, S.T., Kr, B. and Duggal, S.K., 2012. Study of waste plastic mix concrete with plasticizer. ISRN Civil Engineering, 2012.

15- Ferreira, L., de Brito, J. and Saikia, N., 2012. Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. Construction and Building Materials, 36, pp.196-204.

16- Babu, D.S., Babu, K.G. and Tiong-Huan, W., 2006. Effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete. Cement and Concrete Composites, 28(6), pp.520-527.

17- Hannawi, K., Kamali-Bernard, S. and Prince, W., 2010. Physical and mechanical properties of mortars containing PET and PC waste aggregates. Waste Management, 30(11), pp.2312-2320.

18- Saikia, N. and Brito, J.D., 2013. Waste polyethylene terephthalate as an aggregate in concrete. Materials Research, 16(2), pp.341-350.

19- Sabaa, B. and Ravindrarajah, R.S., 1997. Engineering properties of lightweight concrete containing crushed expanded polystyrene waste. Adv Mater Cem Compos.

20- Chen, B. and Liu, J., 2004. Properties of lightweight expanded polystyrene concrete reinforced with steel fiber. Cement and Concrete Research, 34(7), pp.1259-1263.

21- Fraj, A.B., Kismi, M. and Mounanga, P., 2010. Valorization of coarse rigid polyurethane foam waste in lightweight aggregate concrete. Construction and Building Materials, 24(6), pp.1069-1077.

22- Babu, K.G. and Babu, D.S., 2003. Behaviour of lightweight expanded polystyrene concrete containing silica fume. Cement and Concrete Research, 33(5), pp.755-762.

23- Togay, O., Lei, G. and Aliakbar, G., 2017. Short-Term Mechanical Properties of Concrete Containing Recycled Polypropylene Coarse Aggregates under Ambient and Elevated Temperature. Journal of materials in Civil Engineering, 29(10).

24- Alqahtani, F.K., Khan, M.I., Ghataora, G. and Dirar, S., 2016. Production of Recycled Plastic Aggregates and Its Utilization in Concrete. Journal of Materials in Civil Engineering, p.04016248.

25- Alqahtani, F.K., Ghataora, G., Khan, M.I. and Dirar, S., 2017. Novel lightweight concrete containing manufactured plastic aggregate. Construction and Building Materials, 148, pp.386-397.

26- Alqahtani, F. K., Khan, M. I., and Ghataora, G., 2014. U.S. Patent No. 8,921,463. Washington, DC: U.S. Patent and Trademark Office.

27- ASTM International, 2014. Standard Specification for Lightweight Aggregates for Structural Concrete. ASTM C330/C330M-14, West Conshohocken, PA, USA.

28- ASTM International, 2016c. Standard specification for Portland cement. ASTM C150/C150M-16, West Conshohocken, PA, USA.

29- ASTM International, 2015. Standard test method for relative density (specific gravity) and absorption of coarse aggregate. ASTM C127-15, West Conshohocken, PA, USA.

30- ASTM International, 2014. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM C136/C136M-14, West Conshohocken, PA, USA.

31- ASTM International, 2016. Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate. ASTM C29/C29M-16, West Conshohocken, PA, USA.

32- ASTM International, 2015. Standard Test Method for Relative (Specific Gravity) and Absorption of Fine Aggregate. ASTM C128-15, West Conshohocken, PA, USA.

33- American Concrete Institute (ACI Committee 211), 1998. Standard Practice for Selecting Proportions for Structural Lightweight Concrete. ACI 211.2-98 (Reapproved 2004), Farmington Hills, MI.

34- ASTM International, 2016. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM C192/C192M-16a, West Conshohocken, PA, USA.

35- ASTM International, 2015. Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM C143/C143M-15a, West Conshohocken, PA, USA.

36- ASTM International, 2016. Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. ASTM C138/C138M-16a, West Conshohocken, PA, USA.

37- ASTM International, 2012. Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method. ASTM C944/C944M-12, West Conshohocken, PA, USA.

38- ASTM International, 2014. Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. ASTM C157/C157M-08(2014), West Conshohocken, PA, USA.

39- British Standards Institution, 2011.Testing concrete: Method for determination of water absorption. BS EN 1881-122:2011, UK.

40- ASTM International, 2012. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. ASTM C1202-12, West Conshohocken, PA, USA.

41- Jansen, D., Kiggins, M., Swan, C., Malloy, R., Kashi, M., Chan, R., Javdekar, C., Siegal, C. and Weingram, J., 2001. Lightweight fly ash-plastic aggregates in concrete. Transportation Research Record: Journal of the Transportation Research Board, (1775), pp.44-52.

42- Slabaugh, S., Swan, C. and Malloy, R., 2007. Development and properties of Foamed Synthetic Lightweight Aggregates. World of coal ash.

43- Al-Manaseer, A.A. and Dalal, T.R., 1997. Concrete containing plastic aggregates. Concrete International, 19(8), pp.47-52.

44- Rahman, M.M., Islam, M.A. and Ahmed, M., 2012. Recycling of waste polymeric materials as a partial replacement for aggregate in concrete. In International Conference on Chemical, Environmental and Biological Sciences.

45- Choi, Y.W., Moon, D.J., Chung, J.S. and Cho, S.K., 2005. Effects of waste PET bottles aggregate on the properties of concrete. Cement and Concrete Research, 35(4), pp.776-781.

46- Klieger, P., 1994. Significance of tests and properties of concrete and concrete-making materials (Vol. 169). ASTM International.

47- Hyodo, H., Tanimura, M., Sato, R. and Kawai, K., 2013, August. Evaluation of Effect of Aggregate Properties on Drying Shrinkage of Concrete. In Third International Conference on Sustainable Construction Materials and Technologies, Kyoto, Japan.

48- Khairallah, R.S., 2009. Analysis of Autogenous and Drying Shrinkage of Concrete.