

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

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

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35
36 **ABSTRACT**

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

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

55 **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

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65 1.0 Introduction

66 Growth of population, increasing urbanization and rising standards of living have contributed
67 to an increase in the quantity of plastic wastes generated through different activities. The
68 growth of the plastic industry has been massive throughout the world, from around 5 million
69 tonnes (Mt) in the 1950s to approximately 322 Mt in 2015 [1, 2]. In the USA, around 32 Mt
70 of plastic waste was generated in 2012, which accounts for 12.7 % of the total municipal
71 solid waste [3]. However, the recycling rate is still not encouraging as compared to the
72 quantity of plastic waste produced each year. In the USA, plastic recycling started in 1980,
73 with a recycling rate of 0.3%, which despite technological advances and a more aware
74 society, in 2012 was still just 8.8% [3, 4]. The remaining quantity is either burnt or disposed
75 of into the landfills, occupying a large area of land, which poses major environmental issues.
76 Many plastic wastes are non-biodegradable wastes that remain in the landfills for hundreds or
77 even thousands of years before they decompose [5].

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

85 In recent years, many studies have been carried out to investigate the effect of using shredded
86 plastic or plastic particles directly as a replacement for normal coarse aggregate (CA) or fine
87 aggregate (FA) on the properties of concrete [6 – 14]. These studies show that the
88 workability, density and mechanical performance of the modified concrete were reduced,
89 while little was reported regarding its durability performance. It has been reported that

90 abrasion resistance was improved by 37 and 33% as a replacement for total aggregate and CA
91 directly, with polyethylene terephthalate (PET) at 7.5 and 15% replacement levels,
92 respectively [15, 9]. According to Ferreira et al. (2012), this increase was because of the
93 higher degree of roughness or fibrous texture given by its plastic particles. The water
94 absorption of concrete made with plastic particles or shredded plastic at various levels (i.e.
95 varying between 15 and 50%) of replacement for normal CA or FA was increased in the
96 range of 17 to 55%, as reported by other researchers [6,16, 17, 18]. The authors attributed this
97 increase to the failure of the two aggregates to mix properly within the matrix of the concrete,
98 causing higher porosity in the matrix. Similarly, it was found that replacing either CA and/or
99 FA with plastic increased drying shrinkage, due to the lower restraint of the plastic particles
100 against the shrinkage of the cement paste [19, 20, 21]. Moreover, Kou et al. (2009) indicated
101 that the resistance of concrete to chloride ion penetration increased by 36.2% when normal
102 FA was replaced with crushed polyvinylchloride (PVC) pipes at 45%. Similarly, Babu and
103 Babu (2003) obtained very low permeability of concrete (i.e. charge passed varying between
104 400 and 700 Columbus) at different replacement levels (i.e. from 20 to 37%) of total
105 aggregate with expanded polystyrene (EPS) [22]. **In addition, in a recent using the short-term
106 mechanical performance of concrete using the recycled plastic aggregate under elevated
107 temperatures has been studied** [23]. However, as per the author's knowledge, the durability
108 aspect of concrete incorporating lightweight aggregate produced by plastic is limited.

109 In the previous works carried out by the authors of the current study, different compositions
110 of synthetic aggregates were developed and incorporated in concrete either as a total or
111 partial replacement for CA [24, 25]. These studies indicated the superior behaviour of
112 synthetic aggregate concrete (synthetic aggregate made using 30% LLDPE and 70% red dune
113 sand) in terms of mechanical performance and therefore, this type of concrete was selected

114 for carrying out further investigation to evaluate its resistance against abrasion, drying
115 shrinkage and durability performance at different replacement ratios.

116 In the present experimental study the use of synthetic aggregate (i.e. SA) as a replacement for
117 pumice lightweight coarse aggregate (PA) at various replacement levels (at 25, 50, 75 and
118 100%) and, as a replacement for Lytag aggregate (LA) at 100% was inspected. Accordingly,
119 the influence of increasing the replacement percentages of either the PA or LA with SA on
120 the hardened and durability properties of concrete at a constant W/C of 0.50 was examined.
121 In addition, analytical correlations between compressive strength and other properties (i.e.
122 abrasion, chloride permeability) were developed.

123 **2.0 Development of synthetic aggregate**

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

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

133 The new aggregate (SA) was used as a coarse aggregate with a nominal maximum size of 10
134 mm, similar to those of the PA and LA. The particle shapes of the SA were sub angular as
135 compared to the angular and rounded shapes of PA and LA respectively (Fig. 1). The texture
136 was partially rough (fibrous), porous and smooth for the SA, PA and LA respectively, as
137 shown in Figure 1. Table 1 and Table 2 show an insignificant difference in the unit weight of

138 the SA and PA or LA; whereas, water absorption of the SA was 85 and 84% lesser compared
 139 to the PA and LA, respectively.



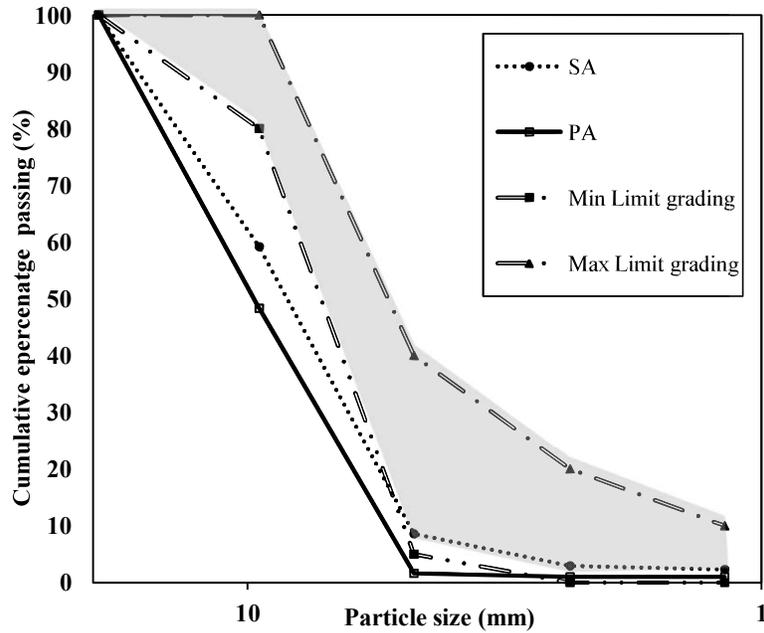
140 Figure 1: Various types of coarse aggregate used in this study: PA; LA; and SA

141 The particle size distribution curve for SA (Fig. 2) was obtained in line with ASTM
 142 C330/C330M-14 in comparison with the PA and the lightweight aggregate grading limits
 143 [27]. The grading of the LA was prepared in the laboratory to match that of the PA because it
 144 was supplied in a range of single sizes by the manufacturer.

145 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

146



147

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

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

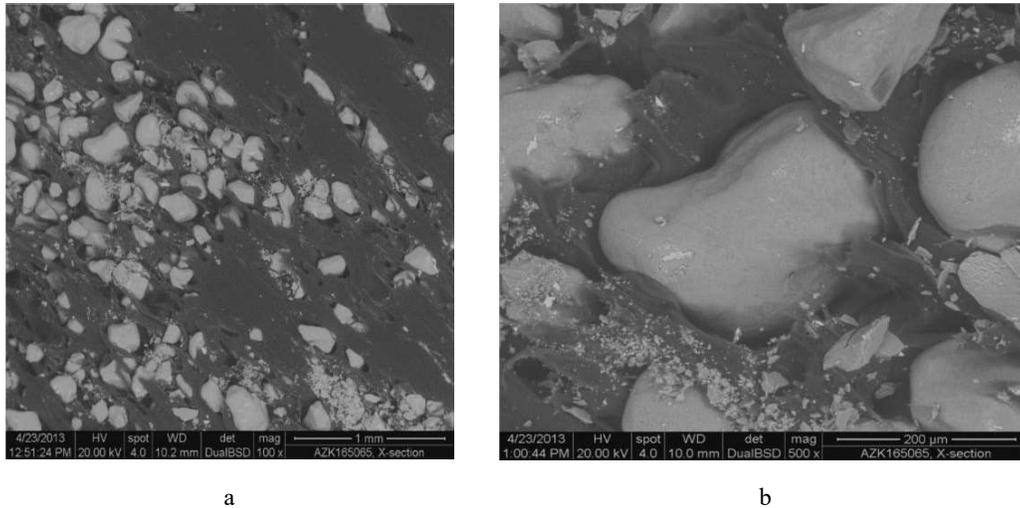


Figure 3: Scanning electron microscopy of SA made with red sand (magnification: 100× (a); 500× (b))

156 3.0 Materials and methods

157 3.1 Materials

158 3.1.1 Cement

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

162 3.1.2 Aggregates

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

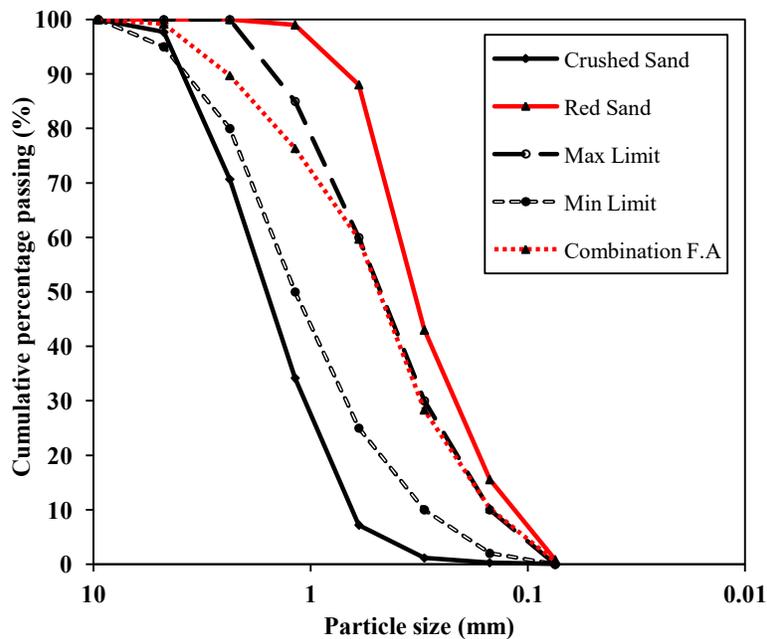
170 As shown in Figure 4, fine aggregate was used in a combination of red sand and crushed sand
 171 with a proportion of 65% and 35% respectively to meet the ASTM C136/C136M-14 [30].

172 The unit weight, specific gravity and water absorption of the fine aggregate were measured
 173 according to ASTM C29/C29M-16 and ASTM C128-15 respectively [31, 32]. The values of
 174 these properties are listed in Table 2.

175 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

176



177

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

180 3.2 Mix proportions

181 In this study, six concrete mixes were designed at a constant W/C ratio of 0.50. The CM1 (as
 182 a natural lightweight control mix) was proportioned in accordance with ACI 211.2-98 [33].

183 For comparison purposes, another control mix (CM2) was designed using Lytag aggregate

184 (as a manufactured lightweight control mix). CM1 and CM2 mixes were prepared using
 185 natural pumice lightweight aggregates and Lytag aggregates respectively. The remaining four
 186 mixes were casted by replacing SA for PA at 25, 50, 75 and 100% replacement levels.

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

192 These mixes were prepared, cast and cured in accordance with ASTM C192/C192M-16a
 193 [34]. Table 3 illustrates the mixture proportions for the mixes per m³. In this table, the
 194 designation “MX” refers to synthetic aggregate concrete made at X volume replacement of
 195 the PA with SA.

196 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	-

197

198 3.3 Tests conducted and methods

199 In this investigation, fresh concrete properties, including slump and fresh density were
 200 measured in accordance to ASTM C143/C143M-15 and ASTM C138/C138M-16,
 201 respectively [35, 36]. Concrete compressive strength tests were conducted using a 100 by 200
 202 mm cylinder in accordance with ASTM C39/C39M-16; while, 50 by 100 mm cylinder

203 specimens were used for splitting tensile strength tests as specified in the ASTM
204 C496/C496M-11. The resistance of concrete against abrasion was evaluated for 200 × 200 ×
205 50 mm specimens in line with procedures described in ASTM C944/C944M-12 [37]. Drying
206 shrinkage of hardened concrete prisms of 75 × 75 × 285 mm was conducted in accordance to
207 ASTM C157/C157M-08 [38]. Furthermore, the flexural deformation was measured for a
208 single point loading prism using an INSTRON machine (model 3367), as shown in Figure 5.
209 In this test, load was applied vertically at 0.2 mm/min and simultaneously the respective
210 increase in the deflection was measured and recorded directly by the machine.



211

F

212 Figure 5: Failure deformation test setup using INSTRON machine

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

219 4.0 Results and discussion

220 4.1 Fresh properties

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

222

223 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

224

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

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

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

242

243 **4.2 Hardened properties**

244 **4.2.1 Mechanical properties**

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

247 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

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

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

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

261 75 and 100% of CA and FA with plastic based aggregates decreased splitting tensile strength
262 by 33 and 26%, respectively.

263 Generally, the reduction in mechanical properties is attributed to the poor bonding between
264 the cement paste and the SA, which decreases the resistance of the matrix against the load
265 and thereby increases the concentration of stress around the aggregate particles. This poor
266 bonding results from the hydrophobic nature of SA due to the presence of plastic in its matrix
267 [11, 13, 14].

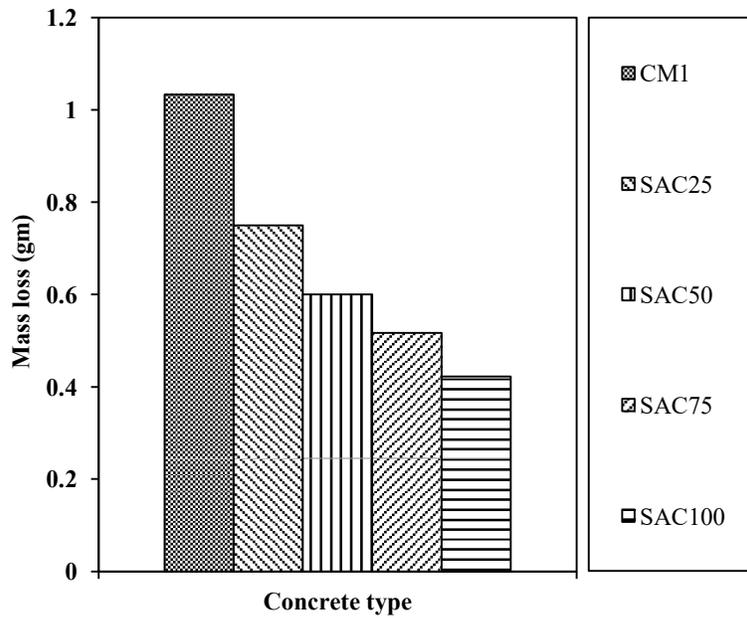
268 The SAC mixes containing 25, 50 and 75% replacement levels had compressive strength
269 results higher than the minimum requirements (17 MPa) of the ASTM C330/C330M (Table
270 6). Furthermore, the SAC mixes with 25 and 50% replacement levels had a splitting tensile
271 strength higher than the minimum requirements (2.1 MPa) of the ASTM C330/C330M.
272 However, of these mixes, only SAC25 meets the density, compressive strength and splitting
273 tensile strength requirements given in Table 6. Thus, these results confirm the potentiality of
274 SAC25 as a promising structural lightweight concrete mix; where both a low density and
275 moderate strength is required.

276 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

277 4.2.2 Abrasion resistance

278 Figure 6 shows the results of the 28-day abrasion of SAC mixes compared with that of CM1.
279 The CM1 had a mass loss of 1.03gm; while the mass loss of SAC mixes ranged from 0.42 to
280 0.75 gm.



281

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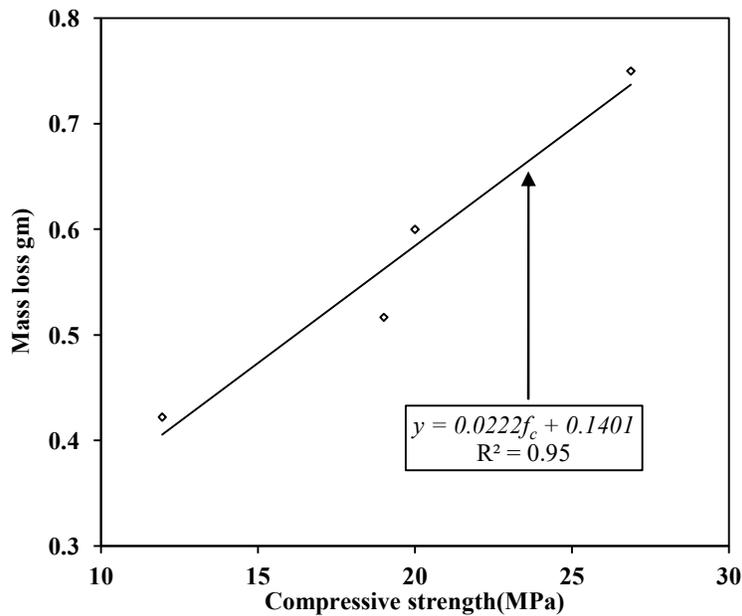
Figure 6: Results of mass loss of SACs and CM1 at 28 day

283 As shown in Figure 6, the reduction in abrasion of SAC mixes compared to that of CM1
 284 ranged from 29 to 58% (0.28 to 0.61 gm) as the substitution level of PA with SA increased
 285 from 25 to 100%. These results are in agreement with the findings of Ferreira et al. (2012)
 286 and Saikia and de Brito (2014) who reported an abrasion resistance increase of 28-42% as a
 287 result of replacing 7.5-15% of CA and FA with plastic particles [9, 15] . The possible reason
 288 for the reduction in abrasion of SAC is the increase in the resistance of its aggregate particles
 289 (SA) towards abrasion due to its plasticity nature together with its fibrous surface texture
 290 [15].

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

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

301
$$y = 0.0222 f_c + 0.1401 \quad (\text{Eq. 1})$$



302

303 Figure 7: Correlation between mass loss and compressive strength

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

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

311

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

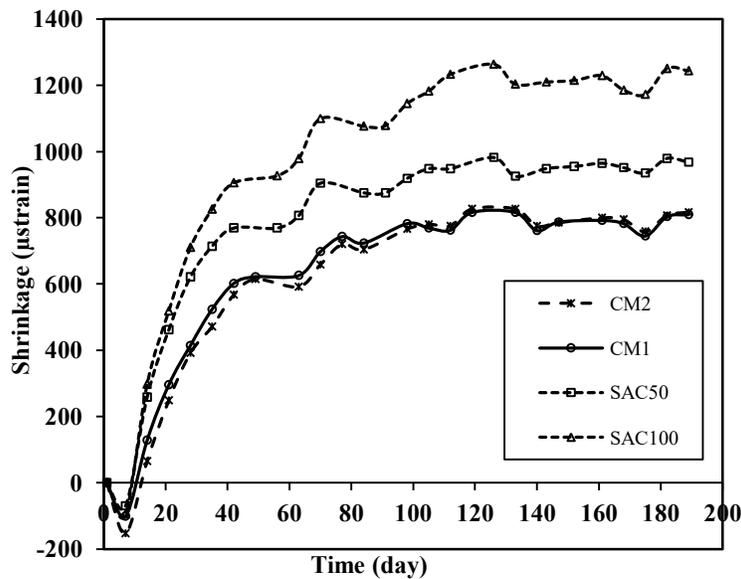
Concrete type	Percentage difference between the predicted and experimental results
	Eq. 1
SAC25	-1.7
SAC50	-2.6
SAC75	8.9
SAC100	-3.9

312

313 4.2.3 Drying shrinkage

314 The results of the drying shrinkage for SAC50 and SAC100 in comparison with CM1 and

315 CM2 are shown in Figure 8.



316

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

318 Figure 8 shows that the increase in the drying shrinkage of the SAC mixes compared with

319 that of CM1 ranged from 36 to 58%, 17 to 46% and 19 to 54% at 28, 91 and 182 days of air

320 curing respectively, as the replacement level was increased from 50 to 100%. Additionally,

321 SAC100 had a drying shrinkage that was 75%, 49% and 52% higher than that of CM2 at 28,

322 91 and 182 days of air curing respectively.

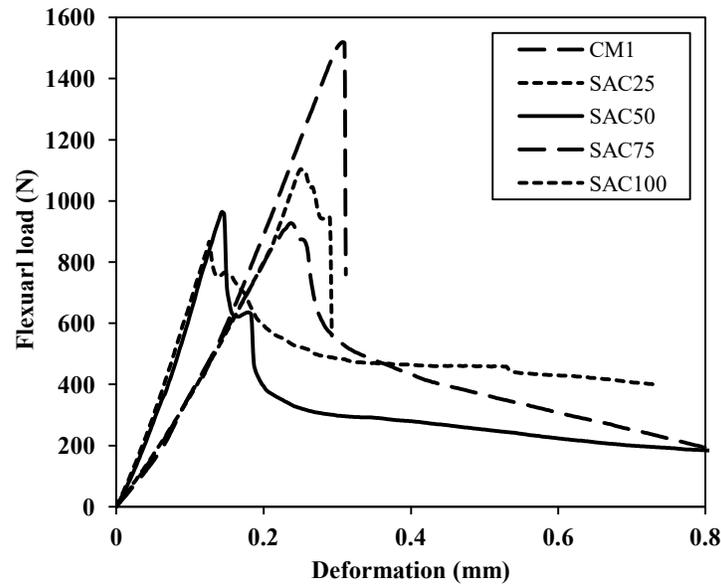
323 The amount of drying shrinkage is controlled by water loss. However, as only the matrix
324 loses the water, consequently the increase in drying shrinkage of SAC mixes, as compared to
325 the control mixes is because of the weaker bond between the cement matrix and
326 manufactured aggregates than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

334 Nonetheless, the increase in drying shrinkage of the SAC mixes is still lower than that
335 reported elsewhere [20, 21]; where replacing 45 and 55% of CA and both aggregates (CA,
336 FA) with plastic particles increased the 28 and 90 day drying shrinkage by 149 and 78%,
337 respectively. Furthermore, the drying shrinkage achieved by the SAC mixes is in agreement
338 with that reported for normal weight concrete [47, 48]; where drying shrinkage of 800 to
339 1000 μ strain was observed at different drying periods (119 to 182 days). Thus, the present
340 study results suggest that the drying shrinkage given by the SAC mixes becomes acceptable
341 with respect to the application of these types of concrete when compared to the normal
342 concrete performance.

343 **4.2.4 Flexural deformation**

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

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



351

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

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

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

362 lightweight applications where a low density, moderate strength and high deformation are
363 required.

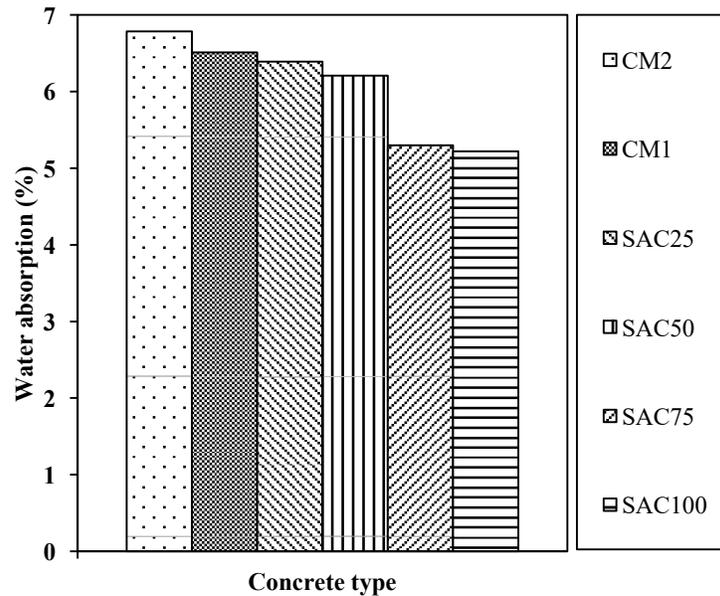
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366 4.3 Durability properties

367 4.3.1 Water absorption

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



371

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

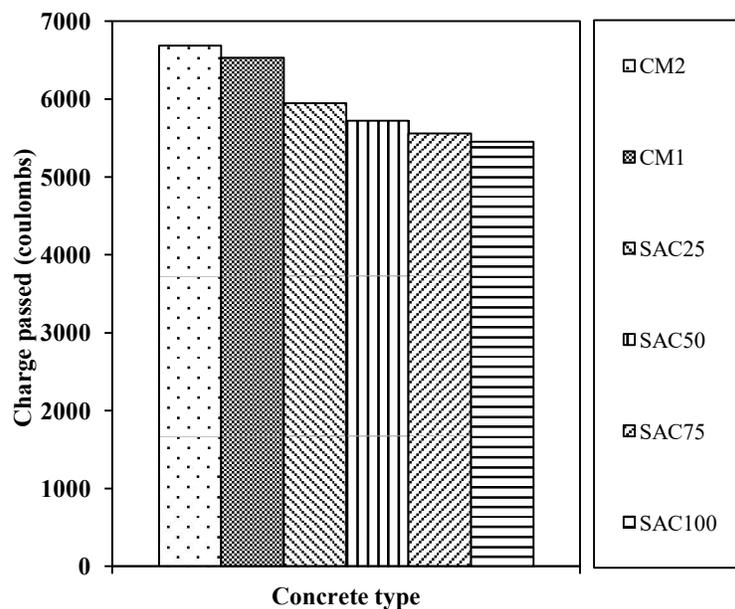
373 The decrease in the water absorption of the SAC mixes compared with that of CM1 ranged
374 from 5 to 20%, as the replacement level increased from 25 to 100%. Similarly, SAC100 had a
375 28-day water absorption 23% less than that of CM2. The decrease in the water absorption
376 values is due to the lower water absorption of new synthetic aggregate (85%) than that of PA
377 and LA (Tables 1 and 3). This observation is consistent with the finding of Babu et al. (2006)

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

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

385 4.3.2 Chloride permeability

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



388

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

390 Figure 11 shows the reduction in 28-day chloride permeability of SAC mixes compared with
391 that of CM1 ranged from 9 to 17% as the replacement level of PA with SA increased from 25
392 to 100%. Additionally, SAC100 had 28-day chloride permeability 18% lesser than that of
393 CM2. These results are in line with the previous studies of chloride permeability reductions

394 of 43 and 36% as a result of substituting 37 and 45% of total aggregates (CA, FA) and FA
395 with plastic particles, respectively [11, 22].

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

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

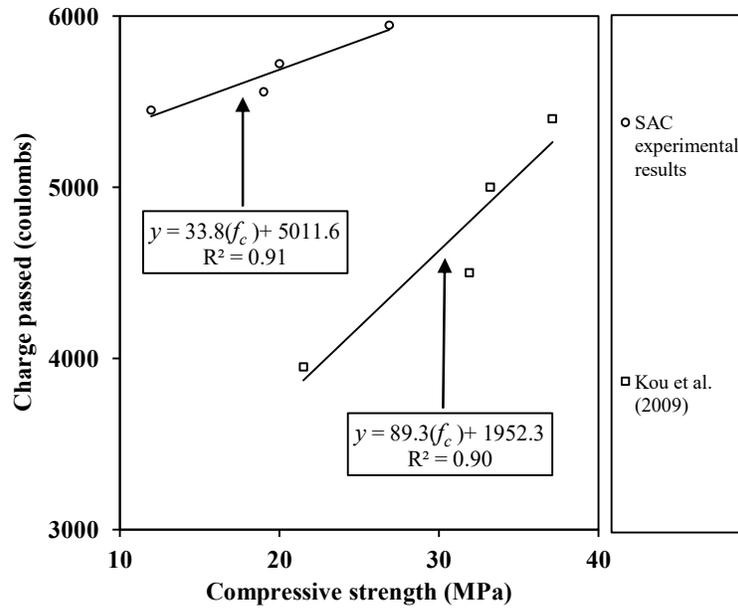
407 Furthermore, in this study, the experimental results of the SAC mixes presented in Figure 12
408 were used to explore the correlation between the charge passed (y) and the cylinder
409 compressive strength (f_c) at 28 days. Results of Kou et al.'s (2009) study were also used to
410 develop a correlation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

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

$$413 \quad y = 33.8(f_c) + 5011.6 \quad (\text{Eq. 2})$$

$$414 \quad y = 89.3(f_c) + 1952.3 \quad (\text{Eq. 3})$$

415



416

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

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

420 Table 8 presents the percentage difference between the predictions of Equations 2 to 3 and
 421 the experimental results. As shown in Table 8, Equation 2 exhibits good estimates, i.e. within
 422 $\pm 1.7\%$ for the chloride permeability of the SAC mixes. On the other hand, Kou's model
 423 substantially underestimates the chloride permeability of the SAC mixes by 26.8 to 44.6%.
 424 This difference is mainly because of the dissimilarity in the experimental conditions,
 425 including all parameters of mixes.

426 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

427

428 5.0 Conclusions

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

434 • The synthetic aggregate concretes were found to have less consistency as compared to
435 the control mixes. The slump of SAC mixes was lower by 11-23% as compared to the
436 CM1, and it was 31% lower than that of CM2. Low water absorption and angular
437 particle shapes of SA caused the decrease in the values of slump.

438 • The synthetic aggregate concretes showed lower mechanical performance as
439 compared to natural lightweight aggregate concrete and Lytag aggregate concrete.
440 The decrease in the 28-day compressive and splitting tensile strength of SAC mixes
441 compared to that of CM1 ranged from 15 to 62% and from 12 to 31% respectively, as
442 the replacement level was increased from 25 to 100%. Similarly, 100 % replacement
443 of LA decreased compressive and splitting tensile strength by 63% and 25%
444 respectively. The decrease in the mechanical properties of synthetic aggregate
445 concrete is mainly attributed to the poor bonding between the cement paste and the
446 synthetic aggregate.

447 • The synthetic aggregate concrete had shown better performance against abrasion than
448 control mixes. However, SAC yielded a substantial increase in the drying shrinkage
449 values as compared to control mixes. The 182-day drying shrinkage of the SAC
450 mixes increased by 19-54%, as the replacement level of PA with SA was increased
451 from 50 to 100%. Similarly, replacing LA totally with SA increased the 182-day
452 drying shrinkage by 52%, as compared to the CM2. Moreover, SAC under flexural

453 load has displayed ductile behaviour in contrast with the brittle failure observed for
454 CMI.

455 • The synthetic aggregate concretes showed high durability in terms of water
456 absorption and chloride permeability as compared to that of natural lightweight
457 aggregate concrete and Lytag aggregate concrete. The 28-day water absorption and
458 chloride permeability of SAC mixes decreased by 5-20% and 9-17% respectively,
459 with the increase in replacement level of PA with SA from 25 to 100%. Additionally,
460 at 100% replacement of LA the reduction in water absorption and chloride
461 permeability for SAC was 23 and 18% respectively. In addition, the analytical models
462 for the abrasion and chloride permeability of the synthetic aggregate concretes were
463 also proposed.

464 • The SAC25 could potentially be used as a durable lightweight structural mix where a
465 low chloride level exists as it meets requirements of ASTM C330/C330M-14.
466 However, it is suggested to carry out further detailed and long term mechanical and
467 durability testing, including the environmental and economical evaluation, to verify
468 the potential usage of the synthetic aggregates for civil infrastructure.

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