

# The impact of variation in chemical and physical properties of PFA and BPD semi-dry cement paste on strength properties

Limbachiya, V. , Ganjian, E. and Claisse, P.A.

**Author post-print (accepted) deposited by Coventry University's Repository**

**Original citation & hyperlink:**

Limbachiya, V. , Ganjian, E. and Claisse, P.A. (2015) The impact of variation in chemical and physical properties of PFA and BPD semi-dry cement paste on strength properties.

Construction and Building Materials, volume 96 : 248–255

<http://dx.doi.org/10.1016/j.conbuildmat.2015.08.002>

DOI 10.1016/j.conbuildmat.2015.08.002

ISSN 0950-0618

Publisher: Elsevier

**NOTICE: this is the author's version of a work that was accepted for publication in Construction and Building Materials. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Construction and Building Materials, 96, (2015)] DOI: 10.1016/j.conbuildmat.2015.08.002.**

© 2015, Elsevier. Licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International <http://creativecommons.org/licenses/by-nc-nd/4.0/>

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

**The impact of variation in chemical and physical properties of PFA and BPD  
semi-dry cement paste on strength properties  
(REVISION INCLUDING HIGHLIGHTS)**

Vireen Limbachiya\*, Eshmaiel Ganjian, Peter Claisse

*Coventry University, Faculty of Engineering and Computing, Civil Engineering,  
Architecture and Building, Coventry, UK*

\* Corresponding Author, Email: [limbachv@uni.coventry.ac.uk](mailto:limbachv@uni.coventry.ac.uk)

26 **Abstract**

27 The effect of Pulverised Fuel Ash (PFA )and By-Pass-Dust (BPD) in ternary semi-dry cement pastes  
28 was reported. As well as this, the variability over 6 months in chemical composition and particle  
29 distribution was reviewed to determine impact on strength. The addition of BPD in ternary pastes  
30 resulted in a reduced strength when combined with PFA. PFA and BPD samples obtained over a 6  
31 month period showed variability in both chemical composition and particle distribution. For PFA, it  
32 was reported that at 14 days the particle size distribution had greatest impact on strength and at 28 days  
33 the SiO<sub>2</sub> content had greatest impact. The high variability in BPD particle size distribution resulted in  
34 finer particles achieving the greatest strength.

35

36 **Keyword: Material variability, Pulverised Fuel Ash, By-Pass Dust, Compressive Strength.**

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53 **1. Introduction**

54

55 Pulverized fuel ash (PFA) and by-pass dust (BPD) are not the primary products that  
56 are produced and therefore there is little to no control over the particle size  
57 distribution or chemical composition. Due to this, these materials have the potential to  
58 have a different chemical compositions and particle distribution not only from  
59 different sources but also from the same source over a period of time.

60

61 PFA is made up of very fine; predominantly spherical glassy particles collected in the  
62 dust collection systems from the exhaust gases of fossil fuel power plants [1]. During  
63 the burning of coal for power stations there are two types of ashes produced, PFA is a  
64 finer particle that rises up with the flue gases and bottom ash are the heavier particles  
65 which do not rise. Out of the two ashes, PFA provides better suitability for Ordinary  
66 Portland Cement (OPC) replacement due to its finer particles and greater pozzolanic  
67 reactivity [2].

68

69 BPD contains more cementitious phases when compared with CKD which contains a  
70 higher amount of calcium carbonate [3]. The temperature at which the materials are  
71 obtained also has effect on the chloride salts present and therefore the Loss on  
72 Ignition (LOI), which is likely to be much lower for BPD than CKD. When analysing  
73 past literature all these factors have to be considered and if the LOI was below 10%  
74 CKD was assumed to be BPD, this is due to the LOI for all samples in this study  
75 being below this mark.

76

77 The influence of PFA and its mean particle size on certain engineering properties of  
78 cement composite mortars was investigated [4]. The results showed that the  
79 compressive strength increases as the mean particle diameter decreased. It was also  
80 reported that the early stage strength had the same outcome, which tends to decrease  
81 with the use of PFA. This led to the conclusion that increase in the early age strength,  
82 was due to the use of PFA that has finer particles. Lachemi et al. [5] obtained CKD  
83 (assumed to be BPD) from various sources and reported its use as a cement  
84 replacement in a controlled low strength material. It was concluded that the chemical  
85 composition influenced the fresh, hardened and durability characteristic of a  
86 controlled low strength materials and higher compressive strength was attributed to  
87 the higher free CaO content and lower LOI.

88

89 From an industry perspective, greater concern would come from having variability  
90 from a single source on a monthly basis. Therefore, the aim of this paper is to see the  
91 variation in chemical/physical properties of PFA and BPD obtained on a monthly  
92 basis over a period of 6 months. Thereafter, analyse the effect of these materials on  
93 the compressive strength in semi-dry cement paste. The study also determined the  
94 effect of ternary OPC-PFA-BPD blends in semi-dry cement paste.

95

96

97

98

99

100

101

## 2. Materials

### 2.1 Ordinary Portland cement

The OPC fulfilled the requirements of BS EN 197-1 CEM I [6] and was supplied by Hanson Heidelberg Cement group. Table 1 shows the chemical composition of the OPC.

**Table 1 Chemical composition of OPC**

Composition	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>
Value (%)	19.42	0.36	4.55	2.49	0.02	1.03	60.60	0.22	0.57	0.2	3.62

### 2.2 Pulverised fuel ash (or Fly Ash)

The PFA for this study was obtained from a member of the United Kingdom Quality Ash Association. The physical and chemical properties of the PFA(PFA-T) used in determining the effect of OPC-PFA-BPD blends and the PFA obtained over the 6 months is shown in Table 2 and Table 3, respectively. It can be seen from Table 2 that there is a slight variability in the fineness of PFA from month to month. The difference is not large. However, this does not rule out the fact that if there were to be differences in strengths as replacement level increased, then one of the potential factors for this could be due to samples having finer particles. Li and Wu [5] reported that average particle sizes of PFA increasing from 12.1 to 18.8  $\mu\text{m}$  resulted in 28 day strengths decreasing from 36.4 to 33 MPa.

Table 3 reports on the chemical composition of PFA samples. PFA is a popular replacement material because of its high SiO<sub>2</sub> content which reacts with the secondary

126 calcium hydroxide (CH) from the initial hydration process to produce Calcium-  
 127 Silicate-Hydrate (CSH). The four oxides which make up over 80% of the chemical  
 128 composition are SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and CaO. PFA has greater quantities of SiO<sub>2</sub> and  
 129 the maximum difference was noted between November and August, which had SiO<sub>2</sub>  
 130 quantities of 45.85% and 52.29% respectively. The difference between largest and  
 131 smallest quantity for Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and CaO were 4.67%, 2.83% and 3.32%  
 132 respectively.

133

134 Table 2 and 3 show that although samples were procured from the same source there  
 135 was variability in both chemical composition and fineness on a monthly basis. The  
 136 reasons for this variability could be due to samples being obtained from a different  
 137 manufacturing batch, new batch of raw material being burned, change in machinery  
 138 setting etc. If industry was to implement the use of these materials, this level of  
 139 variability would be likely to occur and therefore it is important to note the effect the  
 140 variability would have on the strength.

141

142 **Table 2 percentage of PFA passing given meshes**

Mesh No	Aperture µm	Passing Below %						
		July	Aug	Sept	Oct	Nov	Dec	PFA
<b>100</b>	<b>150</b>	90	94	91	94	95	90	90
<b>140</b>	<b>106</b>	81	88	82	86	88	81	81
<b>200</b>	<b>75</b>	70	80	72	76	78	70	70
<b>325</b>	<b>45</b>	55	65	58	61	63	55	55
<b>400</b>	<b>38</b>	51	60	53	56	58	50	49

143

144

145

146

147 **Table 3 Chemical composition of PFA from July to December.**

Composition	SiO <sub>2</sub> (%)	TiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	MnO (%)	MgO (%)	CaO (%)	Na <sub>2</sub> O (%)	K <sub>2</sub> O (%)	P <sub>2</sub> O <sub>5</sub> (%)	SO <sub>3</sub> (%)
<b>PFA-JUL</b>	46.53	0.92	24.43	9.12	0.06	1.62	2.81	0.91	2.75	0.29	0.49
<b>PFA-AUG</b>	52.29	0.93	22.57	10.38	0.07	1.44	3.00	0.77	2.35	0.22	0.51
<b>PFA-SEPT</b>	50.49	0.98	22.75	7.55	0.08	1.54	3.95	0.73	2.27	0.37	0.57
<b>PFA-OCT</b>	49.82	0.89	22.08	9.57	0.10	1.53	4.20	0.63	1.97	0.32	0.61
<b>PFA-NOV</b>	45.85	0.82	19.76	8.42	0.10	2.09	6.13	0.79	2.05	0.51	0.84
<b>PFA-DEC</b>	46.78	0.97	21.82	8.46	0.11	1.79	5.12	0.63	2.02	0.35	0.48
<b>PFA-T</b>	47.75	0.97	24.12	10.22	0.16	1.72	3.25	0.73	2.44	0.24	0.65

148

149 **2.3 By- Pass Dust**

150

151 The physical and chemical properties of BPD are reported in Table 4 and Table 5  
 152 respectively. It can be seen from Table 4 that the variability of fineness for BPD is  
 153 larger than that of PFA. Table 4 shows the main difference occurs when the material  
 154 is passed through the 38µm mesh, the largest differences are between the  
 155 September/November and October samples at 32% and 33% respectively.

156

157 Table 5 reports on the chemical composition of BPD samples. The chemical  
 158 composition of BPD is similar to that of OPC; however BPD contained greater  
 159 quantities of alkalis (pH of OPC= 11-13.5 and pH of BPD=12-14) [7] [8] and sulphur  
 160 trioxide (SO<sub>3</sub>). The four oxides which make up over 80% of the composition are CaO,  
 161 SiO<sub>2</sub>, K<sub>2</sub>O and SO<sub>3</sub>. BPD consists largely of CaO as it is fully calcined or calcined to  
 162 a high degree. The largest difference was between July and October, which had CaO  
 163 quantities of 44.03% and 53.13% respectively. The difference between largest and  
 164 smallest quantity for SiO<sub>2</sub>, K<sub>2</sub>O and SO<sub>3</sub> was 4.58%, 5.97% and 7.18% respectively.

165



166 The variability noted for chemical composition and fineness of BPD was larger than  
 167 PFA. This is due to BPD being defined as a 'waste material', while PFA is regulated  
 168 [9] to a degree where it can be used as a cement replacement. This results in no  
 169 control over the material that is provided for use and the variability's stated in  
 170 analysis of PFA occurring to a greater degree.

171 **Table 4 percentage of BPD below given meshes**

Mesh No	Aperture µm	Passing Below %						
		July	Aug	Sept	Oct	Nov	Dec	BPD
100	150	91	96	88	96	86	93	93
140	106	83	89	74	91	73	85	86
200	75	79	78	58	85	57	72	74
325	45	48	56	34	67	34	48	50
400	38	41	48	28	60	27	39	42

172

173 **Table 5 Chemical composition of BPD from July to December.**

Composition	SiO <sub>2</sub> (%)	TiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	MnO (%)	MgO (%)	CaO (%)	Na <sub>2</sub> O (%)	K <sub>2</sub> O (%)	P <sub>2</sub> O <sub>5</sub> (%)	SO <sub>3</sub> (%)
<b>BPD-JUL</b>	12.79	0.19	3.47	1.88	0.04	0.82	44.03	1.16	10.06	0.12	12.22
<b>BPD-AUG</b>	15.58	0.22	4.26	2.26	0.04	0.98	50.32	0.70	5.80	0.13	9.23
<b>BPD-SEPT</b>	14.85	0.20	3.70	2.11	0.04	0.85	47.43	0.88	7.46	0.12	13.42
<b>BPD-OCT</b>	15.13	0.21	3.84	2.24	0.04	0.93	53.13	0.66	5.09	0.14	6.25
<b>BPD-NOV</b>	16.52	0.23	4.17	2.29	0.05	1.11	49.57	0.71	6.29	0.14	11.18
<b>BPD-DEC</b>	17.34	0.20	3.75	2.35	0.05	1.05	52.75	0.52	4.03	0.15	9.94
<b>BPD-T</b>	16.85	0.23	4.16	2.36	0.04	1.04	53.60	0.50	4.28	0.15	6.66

174

### 175 **3. Fabrication**

176

177 The research conducted in this study was part of a programme that was looking at  
 178 concrete paving blocks. Concrete paving blocks differ from normal concrete products  
 179 as they are a semi-dry blend and are compacted and vibrated simultaneously into  
 180 shape. Therefore, the cementitious pastes analysed in this study were also in semi-dry  
 181 form and the cubes made were solely compacted to achieve factory made consistency.

182 The compaction load was defined by comparing results from the industry and  
183 laboratory; this resulted in an accurate reproduction process. The following steps  
184 were taken to produce the 50 mm paste cubes, which has been adopted for casting  
185 standard paving blocks [10].

186 1. The materials were weighed out and mixed before water was added in the  
187 mixer.

188 2. The water was then added to the mix ( w/cm ratio = 0.15)

189 3. It was important to note that the mix was consistent.

190 4. One 50 mm cube mould was placed on top of another and fastened (Figure 1).

191 The reason for this was because of the compaction, more material had to be  
192 inputted then what could manually be fitted into the mould to provide a 50 mm  
193 cube.

194 5. A compaction load of 52 kN for 3 min was applied to the individual cubes  
195 (Figure 2).

196 6. These cubes were then de-moulded and set to cure.

197



198

199

200

201

202



203 **Figure 1 50mm molds construction**

**Figure 2 50mm cube compaction at 52kN**

204

205 The curing procedure replicated the procedure by Ganjian et al. [10]. As stated, once  
206 cast the specimens were covered with a polythene sheet so that there would be no loss  
207 of water. On the next day, all samples were de-moulded and stored in curing

208 chambers at a constant air temperature of  $22 \pm 2^{\circ}\text{C}$  and 98%RH until they were ready  
 209 to be tested. For OPC, PFA and BPD blends, samples were tested at 14 days (due to  
 210 manufacturers requiring early age strength) and for analysing the effect of material  
 211 variability the samples were tested at 14 and 28 days.

212

### 213 3.1 Mix Design

214 The mix design for analysing OPC, PFA and BPD blends was determined by a  
 215 statistical programme. The programme generated the vertices of the constrained  
 216 design space (Lower Limit < Material < Upper Limit) and then calculated the centroid  
 217 point up to the specified degree using Piepel's CONAEV algorithm. From review of  
 218 literature, PFA [11][12][13] and BPD [14][15] can be used effectively but the  
 219 replacement levels at which they can be used varies. As the main aim was to have  
 220 high levels of cement replacement the upper boundaries for OPC, PFA and BPD were  
 221 60%, 80% and 10% respectively, and all lower boundaries were 0%. Figure 3 and  
 222 Table 6 show the simplex plot design and mixes determined for the boundaries set.

223 **Table 6 Mix design for simplex design plot**

224

Mix	OPC (%wt)	PFA (%wt)	BPD (%wt)
1	60	40	0
2	20	80	0
3	37.5	57.5	5
4	23.75	68.75	7.5
5	28.75	68.75	2.5
6	15	80	5
7	60	30	10
8	48.75	48.75	2.5
9	60	35	5
10	10	80	10
11	48.75	43.75	7.5

225

226

227

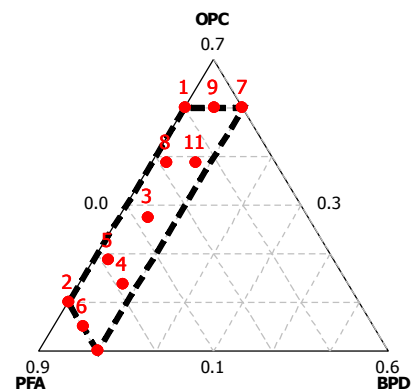
228

229

230

231

**Simplex Design Plot OPC-PFA-BPD**



**Figure 3 Simplex plot design for OPC-PFA-BPD blends**

232

233 The mix design for analysing the effect of material variability is shown in Table 7. In  
 234 this section, PFA was used to replace cement by up to 30% by weight (PFA10= 10%  
 235 by weight) in increments of 10% and BPD was used to replace cement by up to 10%  
 236 by weight (BPD5=5% by weight) in increments of 5%. The reason for producing  
 237 binary mixes was to ensure that changes in strength could be attributed to the variable  
 238 (In this case to PFA/BPD).

239 **Table 7 Mix proportions for PFA and BPD samples**

Mix	July	August	September	October	November	December
<b>Cement:PFA10</b>	90:10	90:10	90:10	90:10	90:10	90:10
<b>Cement:PFA20</b>	80:20	80:20	80:20	80:20	80:20	80:20
<b>Cement:PFA30</b>	70:30	70:30	70:30	70:30	70:30	70:30
<b>Cement:BPD5</b>	95:5	95:5	95:5	95:5	95:5	95:5
<b>Cement:BPD10</b>	90:10	90:10	90:10	90:10	90:10	90:10

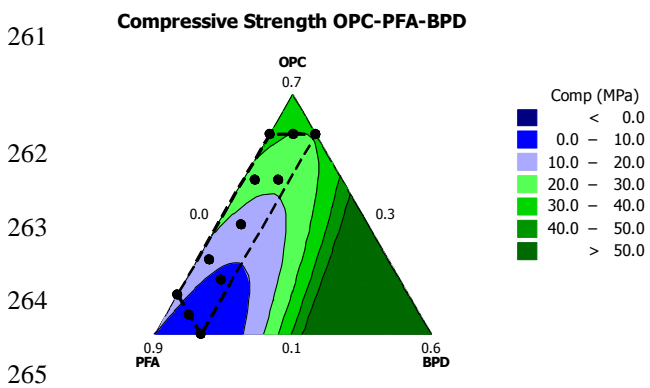
240

#### 241 **4. Results and discussion**

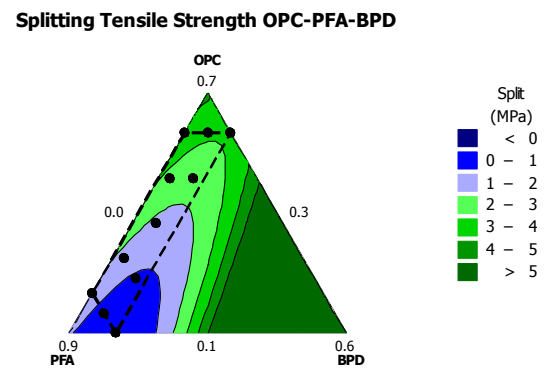
242

243 Figure 4 and 5 shows the 14 day compressive and splitting tensile strength contour  
 244 plots respectively. It is important to note that the contours are only accurate within the  
 245 boundaries that are set. The mix that produced the greatest compressive strength (34  
 246 MPa) and splitting tensile strength (3.69 MPa) consisted of 60% OPC and 40% PFA.  
 247 Due to the low percentage of OPC being used, all mixes consisting of BPD were in  
 248 forms of ternary paste. The effect of BPD can be seen when analysing mixes 1, 7 and  
 249 10 in which OPC content remains the same and BPD is used to replace PFA by 0%,  
 250 5% and 10% respectively. The results showed that 5% BPD replacement provided  
 251 very close strengths (31.9 MPa) to that of 0% BPD (34 MPa) and that 10% BPD  
 252 replacement (30 MPa) was lower than both BPD replacements. However no mix  
 253 containing BPD achieved greater strengths than OPC-PFA mix. When comparing

254 Table 1 (chemical properties of OPC) and Table 5 (chemical properties of BPD) it can  
 255 be seen that the chemical composition of the two materials are very similar. The only  
 256 difference between the two is that BPD has higher quantities of alkalis ( $K_2O$ ) and  
 257 sulphates ( $SO_3$ ). As there was no aggregate used in this stage of the research, alkali  
 258 silica reaction could be ruled out as the reason for decreased strength. It is therefore  
 259 assumed that the decrease in strength is due to the high  $SO_3$  content which can  
 260 increase the porosity therefore decrease the strength [16].



266 **Figure 4 Compressive strength contour**  
 267 **plot (OPC-PFA-BPD)**



269 **Figure 5 Splitting tensile strength contour**  
 270 **plot (OPC-PFA-BPD)**

269 In order to determine the accuracy of the model, the regression value was used to  
 270 determine the difference between actual results and predicted results. The P-value was  
 271 obtained at a 95% confidence level and a limit of 0.05 was used to help decide  
 272 whether to reject or fail to reject a null hypothesis. The equations that predicted the  
 273 strength  $F(x)$  and produced the contour plots for compressive strength and splitting  
 274 tensile strength were:

275

276 **Compressive strength**

277 
$$F(x) = 62.2(OPC) + 7.1(PFA) + 784.6(BPD) - 27.3(OPC*PFA) - 879(OPC*CKD) - 979.9(PFA*CKD)$$

278 **Splitting Tensile Strength**

279 
$$F(x) = 6.1(\text{OPC}) + 0.8(\text{PFA}) + 96.3(\text{BPD}) - 1.1(\text{OPC}*\text{PFA}) - 107(\text{OPC}*\text{BPD}) - 120.7(\text{PFA}*\text{BPD})$$

280

281 The  $r^2$  value for compressive strength and splitting tensile strength was 0.96 and 0.95  
282 respectively. As values were above 0.9, it was determined that the contour plots gave  
283 an accurate representation for trends to be noted and validated. The p-values with a  
284 95% confidence level for compressive and splitting tensile strength were 0.005 and  
285 0.02 respectively. As these values were below 0.05 it could be assumed that the  
286 hypothesis determined from the contour plots can confidently be assured.

287

288 Table 8 reports on the compressive strength at 14 and 28 days for PFA and BPD  
289 variability mixes. The compressive strength for the control mix (100% OPC) was 64.3  
290 MPa and 70.7 MPa for 14 and 28 days respectively. The results show that as PFA  
291 levels increased the strengths decreased for all 6 months analysed. The reduction in  
292 strength is assumed to be due to  $\text{SiO}_2$ . It accumulates within the inner PFA particles  
293 where it is unable to react with the excess lime from the initial hydration to produce  
294 C-S-H gel [17], resulting in a slow pozzolanic reaction and dilution effect [18]. In  
295 comparison to the control mix, no mixes containing PFA (PFA10, PFA20 and PFA30)  
296 achieved greater strengths and the sample that came closest to the control mix was the  
297 August sample at 10% replacement. BPD produced greater results than PFA and as  
298 replacement levels increased from 5% to 10% the strengths increased. The chemical  
299 composition of BPD is very similar to that of OPC; however it contains greater  
300 quantities of finer particles. It is therefore assumed that the same compounds as those  
301 produced within hydration by OPC are also produced with BPD, however with finer  
302 particles the reactivity of oxides leads to greater strengths. The greatest compressive

303 strength was achieved with BPD10 (10% by weight replacement) in October which  
 304 had strengths of 70.4 MPa and 76.1 MPa at 14 and 28 days respectively. At 28 days,  
 305 all mixes containing BPD produced greater strengths than the control mix and at 14  
 306 days the mixes with the least passing through the finest mesh (38 $\mu$ m) (September and  
 307 November) were below the strengths of the control mix.

308

309 **Table 8 Compressive strength (MPa) for mixes**

Mix Day	July		August		September		October		November		December	
	14	28	14	28	14	28	14	28	14	28	14	28
<b>Cement: PFA10</b>	55.8	63.4	59.3	68.4	57.0	66.9	58.7	64.5	55.1	60.6	56.0	64.3
<b>Cement: PFA20</b>	52.6	57.9	54.9	60.8	52.5	61.4	54.7	60.4	51.5	59.4	52.1	58.4
<b>Cement: PFA30</b>	45.2	52.9	49.9	57.7	45.9	53.4	48.4	54.6	47.0	52.9	45.9	52.1
<b>Cement: BPD5</b>	61.6	68.0	60.8	68.8	56.5	64.7	63.7	69.7	58.3	65.3	62.5	68.6
<b>Cement: BPD10</b>	64.5	73.2	67.5	74.5	59.8	72.0	70.4	76.1	63.3	72.9	65.3	74.4

310

311 **PFA10**

312 Figures 6-9 show the correlation between SiO<sub>2</sub>/fineness and 14/28 day compressive  
 313 strength for 10% PFA replacement. The fineness correlation is based on the median  
 314 particle size (D<sub>50</sub>). The results show that at 14 days there was greater correlation  
 315 between SiO<sub>2</sub> (r<sup>2</sup>= 0.83) content than the fineness (r<sup>2</sup>= 0.3). At 28 days, the same  
 316 conclusion could be made but this time the gap was much greater between the  
 317 regression values, with SiO<sub>2</sub> having 0.83 and fineness having 0.02. When analysing  
 318 the fineness results it can be seen that results for November was a possible anomaly.  
 319 If they were to be taken out the regression values for 14 and 28 days would be 0.97  
 320 and 0.05 respectively. This would have resulted in 14 day strength being a  
 321 consequence of fineness and 28 day strength being due to the SiO<sub>2</sub> content.

322 It is assumed that the anomaly could be due to the SiO<sub>2</sub> content in November being  
 323 the lowest out of all the samples, even though it had the 2nd highest fineness. The  
 324 reason for this anomaly backs up the assumption that at 10% replacement the SiO<sub>2</sub>  
 325 content is the main reason for strength gain.

326

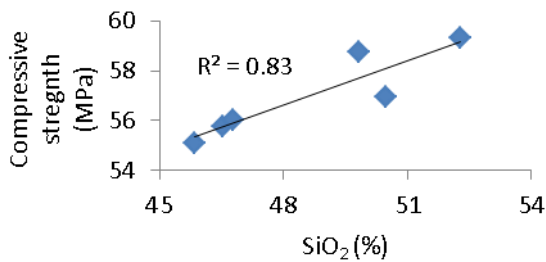
327

328

329

330

331



332 **Figure 6 SiO<sub>2</sub> vs 14 day compressive**

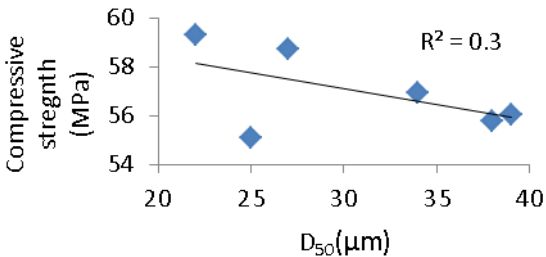
333 **strength PFA10**

334

335

336

337



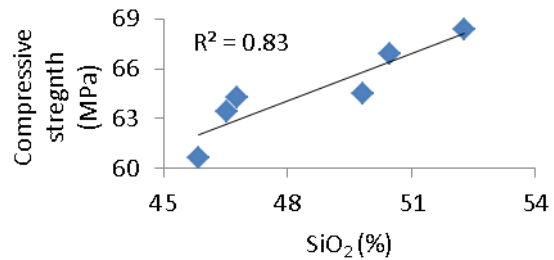
338 **Figure 8 Fineness vs 14 day compressive**

339 **strength PFA10**

340

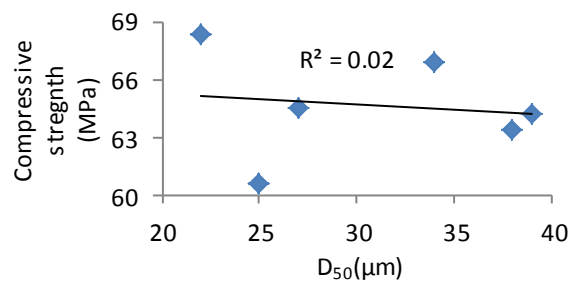
341 **PFA20**

342 Figures 10-13 show the correlation between SiO<sub>2</sub>/fineness and 14/28 days  
 343 compressive strength for 20% PFA replacement. The results show that compressive  
 344 strength at 14 and 28 days, the SiO<sub>2</sub> had regression values of 0.64 and 0.69  
 345 respectively and for the fineness it was 0.26 and 0.33 respectively. The results showed  
 346 at 28 days the correlation between SiO<sub>2</sub> content and strength was not as strong as at  
 347 10% replacement and fineness correlation was slightly higher. A possible reason for



332 **Figure 7 SiO<sub>2</sub> vs 28 day compressive**

333 **strength PFA10**



338 **Figure 9 Fineness vs 28 day compressive**

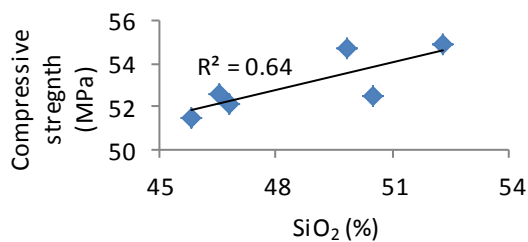
339 **strength PFA10**



348 this could be due to the SiO<sub>2</sub> accumulating deeper within the PFA particles therefore  
 349 needing a longer time to react with the CH to create the extra CSH gel [17]. Therefore  
 350 if a greater quantity of larger PFA particles is added the fineness should have greater  
 351 influence. The same anomaly noted for the November sample at 10% PFA  
 352 replacement was also relevant at 20% replacement. If this value was to be taken out  
 353 then the regression values for fineness against strength would be 0.91 and 0.46 for 14  
 354 and 28 days respectively. This would result in concluding, at 14 days fineness has  
 355 greater effect and at 28 days the SiO<sub>2</sub> has greatest influence.

356

357

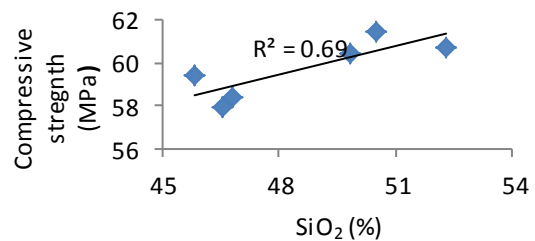


358

359

360

361



362

363

364

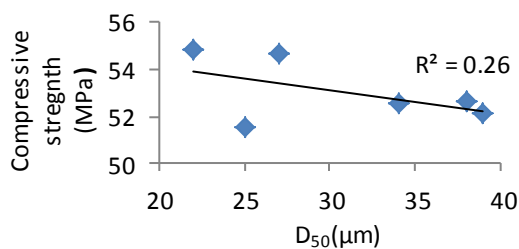
Figure 10 SiO<sub>2</sub> vs 14 day compressive strength PFA20

Figure 11 SiO<sub>2</sub> vs 28 day compressive strength PFA20

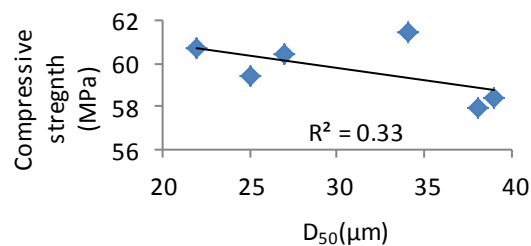
365

366

367



368



369

370

371

Figure 12 Fineness vs 14 day compressive strength PFA20

Figure 13 Fineness vs 28 day compressive strength PFA20

372

**PFA30**

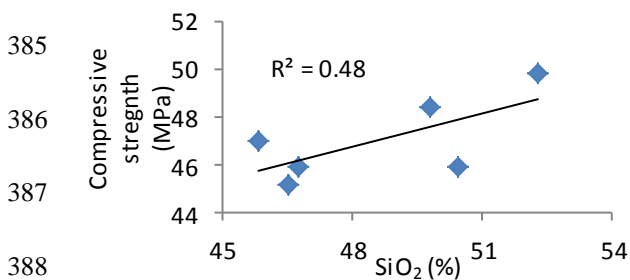
373

374

Figures 14-17 show the correlation between SiO<sub>2</sub>/fineness and 14/28 days compressive strength for 30% PFA replacement. The results show that compressive

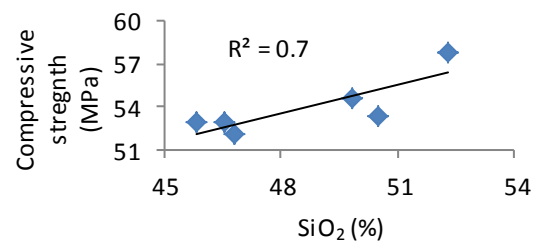
375 strength at 14 and 28 days, the SiO<sub>2</sub> had regression values of 0.48 and 0.7 respectively  
 376 and for the fineness it was 0.78 and 0.55 respectively. The results show that at 14 days  
 377 the fineness has greater influence than SiO<sub>2</sub> and this is believed to be due to the finer  
 378 particles increasing the surface area. At 28 days the SiO<sub>2</sub> content had greater  
 379 correlation with strength however the fineness still had greater correlation than at 10%  
 380 and 20% replacement. Fineness influences strength because the finer the particles  
 381 provide greater reactivity [19] and at 28 days it can be assumed that the PFA content  
 382 has a significant effect on strength as both fineness and SiO<sub>2</sub> content have correlations  
 383 with the strength.

384

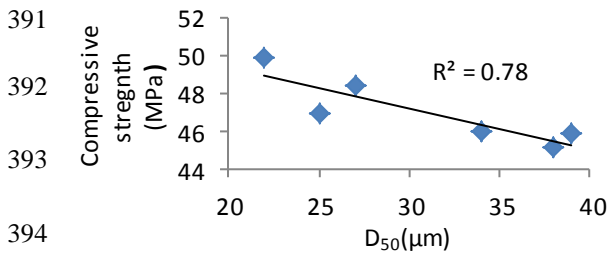


388

389 **Figure 14 SiO<sub>2</sub> vs 14 day compressive**  
 390 **strength PFA30**

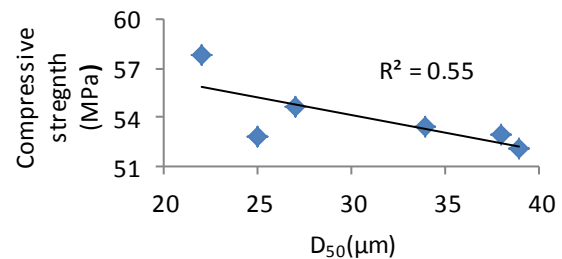


389 **Figure 15 SiO<sub>2</sub> vs 28 day compressive**  
 390 **strength PFA30**



394

395 **Figure 16 Fineness vs 14 day compressive**  
 396 **strength PFA30**



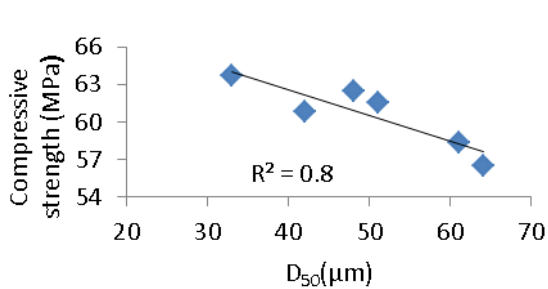
395 **Figure 17 Fineness vs 28 day compressive**  
 396 **strength PFA30**

397

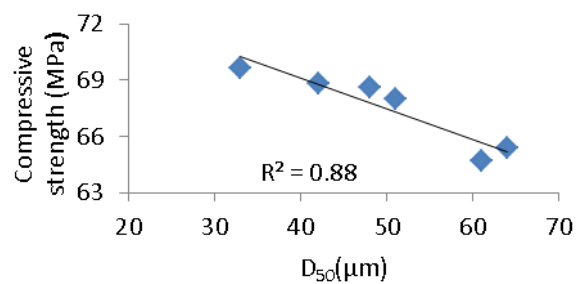
398 **BPD5**

399 Figures 18-21 show the correlation between fineness/SiO<sub>2</sub> + CaO and 14/28 days  
 400 compressive strength for 5% BPD replacement. The results show that at 14 and 28

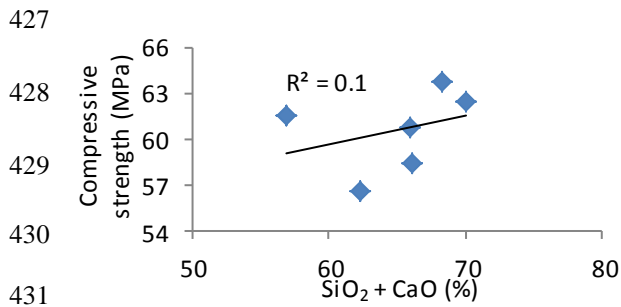
401 days the strength of the paste was dependent on the fineness of the material. Figures  
 402 18 and 19 show that as time increased from 14 to 28 days the correlation increased  
 403 from 0.8 to 0.88, respectively. CaO and SiO<sub>2</sub> are the two predominant oxides within  
 404 BPD and during hydration it is assumed that these oxides are the predominant reason  
 405 for strength increase through the production of CSH [16]. When analysing the  
 406 correlation between chemical properties and strength there was no significant  
 407 correlation between the two, as correlation values were 0.1 for 14 and 28 days. The  
 408 low impact of CaO and SiO<sub>2</sub> content is assumed to be due to the large differences  
 409 within the particle distribution, which results in mixes containing finer particles  
 410 providing a more intense reaction and denser hydrated structures [20] and hence  
 411 greater strengths. The effect of chemical composition can be seen when comparing  
 412 samples obtained in July and December/ September and November as they have very  
 413 similar particle distribution values. For July and December the CaO+SiO<sub>2</sub> content was  
 414 56.82% and 69.68%, respectively and for September and November it was 62.28%  
 415 and 66.09%, respectively. In both comparisons it was noted that the greater content of  
 416 CaO+SiO<sub>2</sub> resulted in a greater strength being achieved.



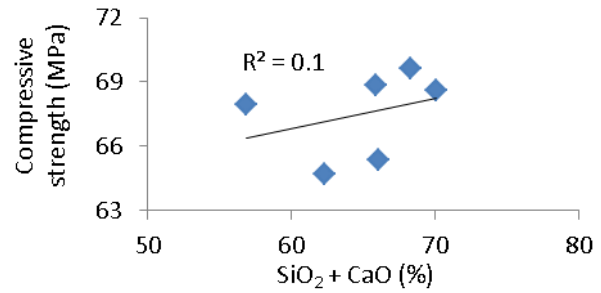
423 **Figure 18 Fineness vs 14 day compressive**  
 424 **strength BPD5**



425 **Figure 19 Fineness vs 28 day compressive**  
 426 **strength BPD5**



432 **Figure 20 SiO<sub>2</sub> +CaO vs 14 day compressive**  
 433 **strength BPD5**



434 **Figure 21 SiO<sub>2</sub> +CaO vs 28 day compressive**  
 435 **strength BPD5**

434

435

436 **BPD10**

437 Figures 22-25 show the correlation between fineness/SiO<sub>2</sub> + CaO and 14/28 days  
 438 compressive strength for 10% BPD replacement. In comparison to 5% replacement,  
 439 10% replacement showed an increase in the regression values for fineness and SiO<sub>2</sub>  
 440 +CaO. The correlation between fineness and compressive strength for 14 and 28 days  
 441 was 0.84 and 0.88, respectively and as noted in BPD5 the fineness of the material  
 442 seemed to dictate the strength achieved. The increase in fineness results in decreased  
 443 strength. The correlation between SiO<sub>2</sub> +CaO and strength at 14 and 28 days was 0.19  
 444 and 0.32, respectively. Although at 10% replacement the oxide content seem to gain  
 445 greater importance in strength development than at 5% the regression values were still  
 446 low. When comparing the July and December/ September and November samples  
 447 which had similar particle distribution values the same trend as noted in 5%  
 448 replacement was noted, in which the samples with greater SiO<sub>2</sub> + CaO content  
 449 produced greater results.

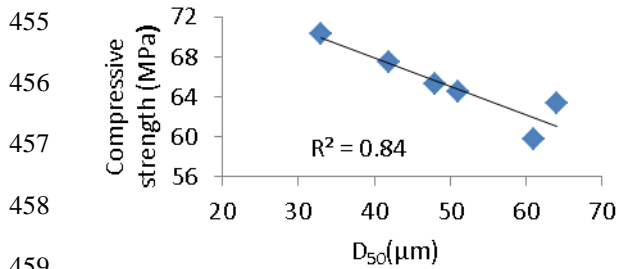
450

451

452

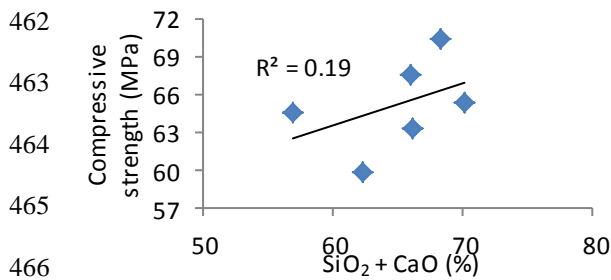
453

454



460 **Figure 22 Fineness vs 14 day compressive**

461 **strength BPD10**



467 **Figure 24 SiO<sub>2</sub> +CaO vs 14 day compressive**

468 **strength BPD10**

469

470

471

## 472 **5. Conclusion**

473

474 The aim of this research was to see the variation in chemical and physical properties

475 of material obtained on a monthly basis over a period of 6 months and to analyse the

476 effect of this on the compressive strength in semi-dry cement paste and the following

477 conclusions were drawn.

478

479 • The addition of BPD in PFA-OPC blends did not results in greater strengths

480 and this is assumed to be due to the high SO<sub>3</sub> content.

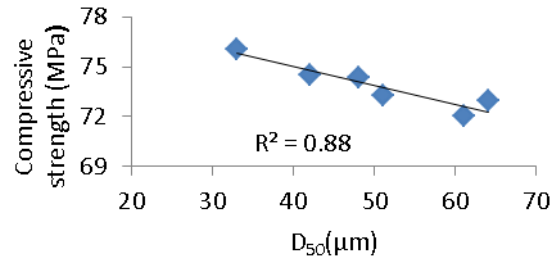


Figure 23 Fineness vs 28 day compressive

strength BPD10

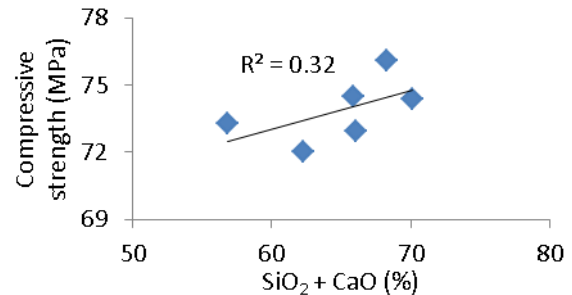


Figure 25 SiO<sub>2</sub> +CaO vs 28 day compressive

strength BPD10

- 481       • For both PFA and BPD the chemical composition of the major oxides had  
482           similar variability's over the 6 months being analysed, however the particle  
483           size distribution was much more variable for BPD than PFA.
- 484       • As PFA levels increased in replacement, the fineness of the material played a  
485           greater role in strength development, in every sample apart from the  
486           November sample at 10% and 20% replacement. The results showed that at 14  
487           days the fineness had greater impact on strength and at 28 days the SiO<sub>2</sub>  
488           content had greater impact on strength.
- 489       • The high variability in BPD particle size distribution played a major role in the  
490           strength development at both 5% and 10% replacement. The samples with  
491           finer particles produced the greatest strength and this is believed to be due to  
492           particle packing as well as finer particles having greater reactivity.
- 493       • PFA and BPD varied from the same source over a period of 6 months on a  
494           monthly basis and this variability affected the strength that was achieved. If  
495           industry was to implement the use of such materials then it is recommended  
496           that the materials chemical composition and to a much greater extent the  
497           particle size distribution is regulated in order to get a suitable range for which  
498           industry could make predicted strengths.

499

500

501

502

503

504

505

506

507 **Reference:**

- 508 [1] Joshi, R. C. - L., R.P. (1997). *Fly Ash in Concrete; Production, Properties and*  
509 *Uses*. Overseas Publishers Association, Amsterdam, The Netherlands.
- 510 [2] Canpolat F, Yilmaz K, Köse MM, Sümer M, Yurdusev MA. (2004) "Use of zeolite, coal  
511 bottom ash and fly ash as replacement materials in cement production". *Cem Concr Res*  
512 *34*, 731-735.
- 513 [3] Ganjian, E, Sadeghi- Pouya, H, Claisse, P, Waddell, M, Hemmings, S, and Johansson,  
514 S. (2008), "Plasterboard and gypsum waste in a novel cementitious binder for road  
515 construction", *Concrete Magazine of concrete society*, 42 (6), 20-22.
- 516 [4] Li, G., and Wu, X. (2005). "Influence of fly ash and its mean particle size on certain  
517 engineering properties of cement composite mortars." *Cem.Concr.Res.*, 35(6), 1128-1134.
- 518 [5] Lachemi, M., Hossain, K. M. A., Shehata, M., and Thaha, W. (2008). "Controlled low  
519 strength materials incorporating cement kiln dust from various sources." *Cem Concr*  
520 *Comp*, 30(5), 381-392.
- 521 [6] BSI (British Standard Institute), BS EN197-1: Cement, part 1: composition,  
522 specifications and conformity criteria for common cement, London, UK, 2011
- 523 [7] Cemex, 2009. *Material safety datasheet: Flue dust Portland Cement*. Rugby: Cemex UK  
524 Operations Ltd.
- 525 [8] Hanson, 2009. *Health and Safety data sheet for Common Cements and Cement*  
526 *Products*, Stamford: Hanson Heidelberg Cement Group.
- 527 [9] British Standards Institution, Specification for pulverized-fuel ash for use with Portland  
528 cement, BS 3892: Part 1, 1993  
529
- 530 [10] Ganjian E, Jalull G, Sadeghi-Pouya H. (2015). "Using waste materials and by-products  
531 to produce concrete paving blocks". *Constr Build Mater.*,77(0), 270-275.

- 532 [11] Papadakis, V. G. (1999). "Effect of fly ash on Portland cement systems: Part I. Low-  
533 calcium fly ash." *Cem.Concr.Res.*, 29(11), 1727-1736.
- 534 [12] Uygunoğlu, T., Topcu, I. B., Gencel, O., and Brostow, W. (2012). "The effect of fly  
535 ash content and types of aggregates on the properties of pre-fabricated concrete  
536 interlocking blocks (PCIBs)." *Constr.Build.Mater.*, 30(0), 180-187.
- 537 [13] Siddique, R., Kapoor, K., Kadri, E., and Bennacer, R. (2012). "Effect of polyester  
538 fibres on the compressive strength and abrasion resistance of HVFA  
539 concrete." *Constr.Build.Mater.*, 29(0), 270-278.
- 540 [14] Siddique, R. (2006). "Utilization of cement kiln dust (CKD) in cement mortar and  
541 concrete—an overview." *Resour.Conserv.Recycling*, 48(4), 315-338.
- 542 [15] Maslehuddin, M., Al-Amoudi, O. S. B., Rahman, M. K., Ali, M. R., and Barry, M. S.  
543 (2009). "Properties of cement kiln dust concrete." *Constr.Build.Mater.*, 23(6), 2357-2361.
- 544 [16] Najim, K. B., Mahmud, Z. S., and Atea, A. M. (2014). "Experimental investigation on  
545 using Cement Kiln Dust (CKD) as a cement replacement material in producing modified  
546 cement mortar." *Constr.Build.Mater.*, 55(0), 5-12.
- 547 [17] Barbhuiya, S. A., Gbagbo, J. K., Russell, M. I., and Basheer, P. A. M. (2009).  
548 "Properties of fly ash concrete modified with hydrated lime and silica  
549 fume." *Constr.Build.Mater.*, 23(10), 3233-3239.
- 550 [18] Wongkeo, W., Thongsanitgarn, P., Ngamjarrojana, A., and Chaipanich, A. (2014).  
551 "Compressive strength and chloride resistance of self-compacting concrete containing high  
552 level fly ash and silica fume." *Mater Des*, 64(0), 261-269.
- 553 [19] Chindaprasirt P, Jaturapitakkul C, Sinsiri T. (2005). "Effect of fly ash fineness on  
554 compressive strength and pore size of blended cement paste". *Cem Concr Comp.*, 27(4),  
555 425-428.
- 556 [20] El-Mohsen MA, Anwar AM, Adam IA. (2015). "Mechanical properties of Self-  
557 Consolidating Concrete incorporating Cement Kiln Dust". *HBRC Journal*, 11(1), 1-6.



558 **Acknowledgements**

559

560 The authors gratefully appreciate and acknowledge the financial support from the 2 Engineering and  
561 Physical Sciences Research Council and Hanson Formpave who have 3 sponsored the PhD programme.

562 The authors also acknowledge the support and facilities that 4 were provided at Coventry University.

563

564