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

Abstract

The effect of Pulverised Fuel Ash (PFA)and By-Pass-Dust (BPD) in ternary semi-dry cement pastes was reported. As well as this, the variability over 6 months in chemical composition and particle distribution was reviewed to determine impact on strength. The addition of BPD in ternary pastes resulted in a reduced strength when combined with PFA. PFA and BPD samples obtained over a 6 month period showed variability in both chemical composition and particle distribution. For PFA, it was reported that at 14 days the particle size distribution had greatest impact on strength and at 28 days the SiO_2 content had greatest impact. The high variability in BPD particle size distribution resulted in finer particles achieving the greatest strength.

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

1. Introduction

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

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

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

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

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

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_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**SO_3**
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 potentials 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 µm 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_2 content which reacts with the secondary calcium hydroxide (CH) from the initial hydration process to produce Calcium-Silicate-Hydrate (CSH). The four oxides which make up over 80% of the chemical composition are SiO_2, Al_2O_3, Fe_2O_3 and CaO. PFA has greater quantities of SiO_2 and the maximum difference was noted between November and August, which had SiO_2 quantities of 45.85% and 52.29% respectively. The difference between largest and smallest quantity for Al_2O_3, Fe_2O_3 and CaO were 4.67%, 2.83% and 3.32% respectively.

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

Table 2 percentage of PFA passing given meshes

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

Table 3 Chemical composition of PFA from July to December.

Composition	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	SO_3 (%)
PFA-JUL	46.53	0.92	24.43	9.12	0.06	1.62	2.81	0.91	2.75	0.29	0.49
PFA-AUG	52.29	0.93	22.57	10.38	0.07	1.44	3.00	0.77	2.35	0.22	0.51
PFA-SEPT	50.49	0.98	22.75	7.55	0.08	1.54	3.95	0.73	2.27	0.37	0.57
PFA-OCT	49.82	0.89	22.08	9.57	0.10	1.53	4.20	0.63	1.97	0.32	0.61
PFA-NOV	45.85	0.82	19.76	8.42	0.10	2.09	6.13	0.79	2.05	0.51	0.84
PFA-DEC	46.78	0.97	21.82	8.46	0.11	1.79	5.12	0.63	2.02	0.35	0.48
PFA-T	47.75	0.97	24.12	10.22	0.16	1.72	3.25	0.73	2.44	0.24	0.65

2.3 By- Pass Dust

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

Table 5 reports on the chemical composition of BPD samples. The chemical composition of BPD is similar to that of OPC; however BPD contained greater quantities of alkalis (pH of OPC= 11-13.5 and pH of BPD=12-14) [7] [8] and sulphur trioxide (SO_3). The four oxides which make up over 80% of the composition are CaO, SiO_2, K_2O and SO_3. BPD consists largely of CaO as it is fully calcined or calcined to a high degree. The largest difference was between July and October, which had CaO quantities of 44.03% and 53.13% respectively. The difference between largest and smallest quantity for SiO_2, K_2O and SO_3 was 4.58%, 5.97% and 7.18% respectively.

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

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

Table 5 Chemical composition of BPD from July to December.

Composition	**SiO_2 (%)**	**TiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**MnO (%)**	**MgO (%)**	**CaO (%)**	**Na_2O (%)**	**K_2O (%)**	**P_2O_5 (%)**	**SO_3 (%)**
BPD-JUL	12.79	0.19	3.47	1.88	0.04	0.82	44.03	1.16	10.06	0.12	12.22
BPD-AUG	15.58	0.22	4.26	2.26	0.04	0.98	50.32	0.70	5.80	0.13	9.23
BPD-SEPT	14.85	0.20	3.70	2.11	0.04	0.85	47.43	0.88	7.46	0.12	13.42
BPD-OCT	15.13	0.21	3.84	2.24	0.04	0.93	53.13	0.66	5.09	0.14	6.25
BPD-NOV	16.52	0.23	4.17	2.29	0.05	1.11	49.57	0.71	6.29	0.14	11.18
BPD-DEC	17.34	0.20	3.75	2.35	0.05	1.05	52.75	0.52	4.03	0.15	9.94
BPD-T	16.85	0.23	4.16	2.36	0.04	1.04	53.60	0.50	4.28	0.15	6.66

3. Fabrication

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

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

1. The materials were weighed out and mixed before water was added in the mixer.
2. The water was then added to the mix (w/cm ratio = 0.15)
3. It was important to note that the mix was consistent.
4. One 50 mm cube mould was placed on top of another and fastened (Figure 1). The reason for this was because of the compaction, more material had to be inputted then what could manually be fitted into the mould to provide a 50 mm cube.
5. A compaction load of 52 kN for 3 min was applied to the individual cubes (Figure 2).
6. These cubes were then de-moulded and set to cure.

Figure 1 50mm molds construction

Figure 2 50mm cube compaction at 52kN

The curing procedure replicated the procedure by Ganjian et al. [10]. As stated, once cast the specimens were covered with a polythene sheet so that there would be no loss of water. On the next day, all samples were de-moulded and stored in curing chambers at a constant air temperature of 22 ± 2°C and 98%RH until they were ready to be tested. For OPC, PFA and BPD blends, samples were tested at 14 days (due to manufacturers requiring early age strength) and for analysing the effect of material variability the samples were tested at 14 and 28 days.

3.1 Mix Design

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

Table 6 Mix design for simplex design plot

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

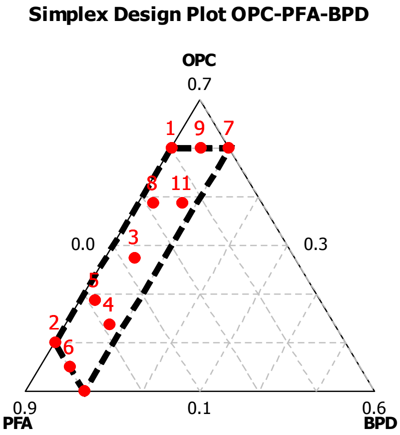


Figure 3 Simplex plot design for OPC-PFA-BPD blends

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

Table 7 Mix proportions for PFA and BPD samples

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

4. Results and discussion

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

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

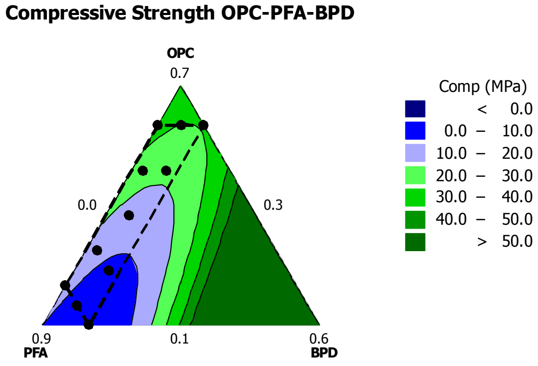


Figure 4 Compressive strength contour plot (OPC-PFA-BPD)

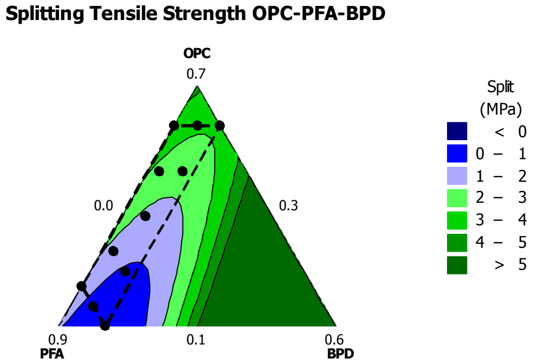


Figure 5 Splitting tensile strength contour plot (OPC-PFA-BPD)

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

Compressive strength

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

Splitting Tensile Strength

$$F(x) = 6.1(OPC) + 0.8(PFA) + 96.3(BPD) – 1.1(OPC*PFA) –107(OPC*BPD) – 120.7(PFA*BPD)$$

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

Table 8 reports on the compressive strength at 14 and 28 days for PFA and BPD variability mixes. The compressive strength for the control mix (100% OPC) was 64.3 MPa and 70.7 MPa for 14 and 28 days respectively. The results show that as PFA levels increased the strengths decreased for all 6 months analysed. The reduction in strength is assumed to be due to SiO_2. It accumulates within the inner PFA particles where it is unable to react with the excess lime from the initial hydration to produce C-S-H gel [17], resulting in a slow pozzolanic reaction and dilution effect [18]. In comparison to the control mix, no mixes containing PFA (PFA10, PFA20 and PFA30) achieved greater strengths and the sample that came closest to the control mix was the August sample at 10% replacement. BPD produced greater results than PFA and as replacement levels increased from 5% to 10% the strengths increased. The chemical composition of BPD is very similar to that of OPC; however it contains greater quantities of finer particles. It is therefore assumed that the same compounds as those produced within hydration by OPC are also produced with BPD, however with finer particles the reactivity of oxides leads to greater strengths. The greatest compressive strength was achieved with BPD10 (10% by weight replacement) in October which had strengths of 70.4 MPa and 76.1 MPa at 14 and 28 days respectively. At 28 days, all mixes containing BPD produced greater strengths than the control mix and at 14 days the mixes with the least passing through the finest mesh (38µm) (September and November) were below the strengths of the control mix.

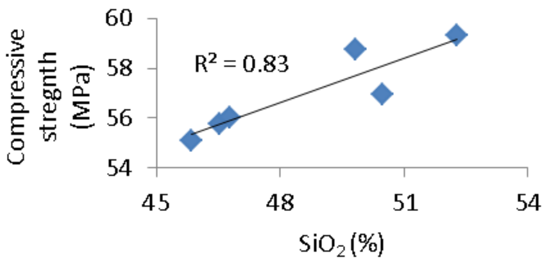
Table 8 Compressive strength (MPa) for mixes

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

PFA10

Figures 6-9 show the correlation between SiO_2/fineness and 14/28 day compressive strength for 10% PFA replacement. The fineness correlation is based on the median particle size (D_{50}). The results show that at 14 days there was greater correlation between SiO_2 ($r^2 = 0.83$) content than the fineness ($r^2 = 0.3$). At 28 days, the same conclusion could be made but this time the gap was much greater between the regression values, with SiO_2 having 0.83 and fineness having 0.02. When analysing the fineness results it can be seen that results for November was a possible anomaly. If they were to be taken out the regression values for 14 and 28 days would be 0.97 and 0.05 respectively. This would have resulted in 14 day strength being a consequence of fineness and 28 day strength being due to the SiO_2 content.

It is assumed that the anomaly could be due to the SiO_2 content in November being the lowest out of all the samples, even though it had the 2nd highest fineness. The reason for this anomaly backs up the assumption that at 10% replacement the SiO_2 content is the main reason for strength gain.



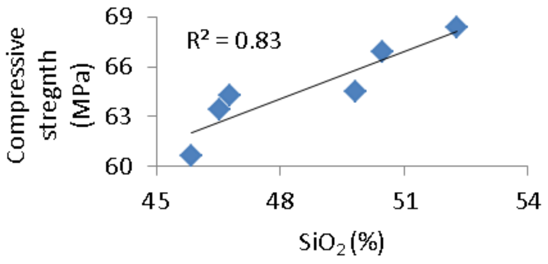
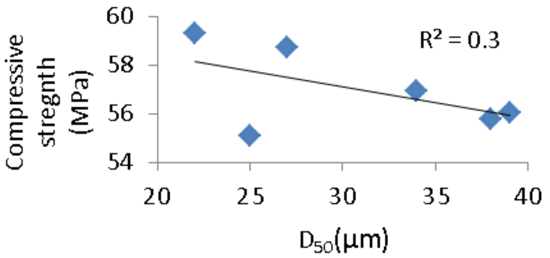


Figure 6 SiO_2 vs 14 day compressive strength PFA10

Figure 7 SiO_2 vs 28 day compressive strength PFA10



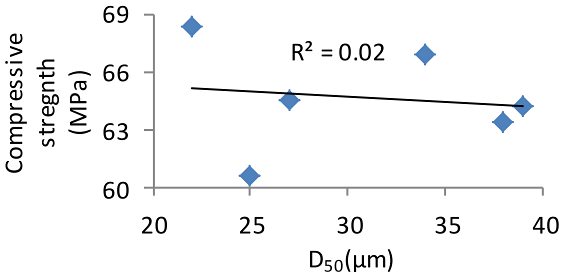
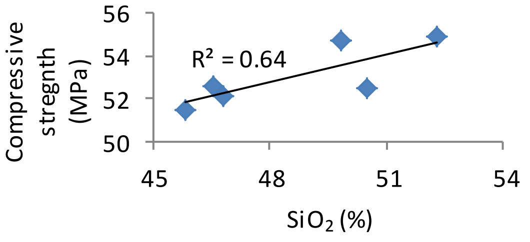


Figure 8 Fineness vs 14 day compressive strength PFA10

Figure 9 Fineness vs 28 day compressive strength PFA10

PFA20

Figures 10-13 show the correlation between SiO_2/fineness and 14/28 days compressive strength for 20% PFA replacement. The results show that compressive strength at 14 and 28 days, the SiO_2 had regression values of 0.64 and 0.69 respectively and for the fineness it was 0.26 and 0.33 respectively. The results showed at 28 days the correlation between SiO_2 content and strength was not as strong as at 10% replacement and fineness correlation was slightly higher. A possible reason for this could be due to the SiO_2 accumulating deeper within the PFA particles therefore needing a longer time to react with the CH to create the extra CSH gel [17]. Therefore if a greater quantity of larger PFA particles is added the fineness should have greater influence. The same anomaly noted for the November sample at 10% PFA replacement was also relevant at 20% replacement. If this value was to be taken out then the regression values for fineness against strength would be 0.91 and 0.46 for 14 and 28 days respectively. This would result in concluding, at 14 days fineness has greater effect and at 28 days the SiO_2 has greatest influence.



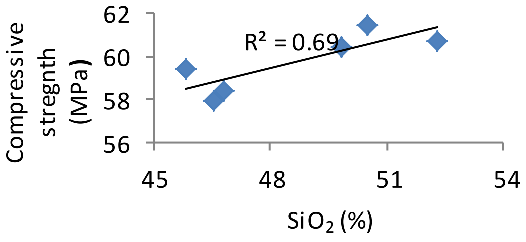
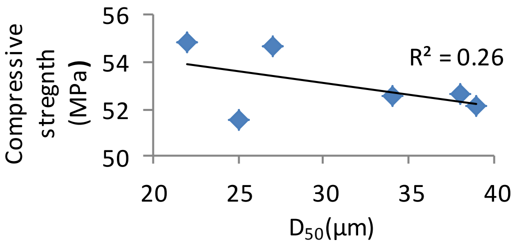


Figure 10 SiO_2 vs 14 day compressive strength PFA20

Figure 11 SiO_2 vs 28 day compressive strength PFA20



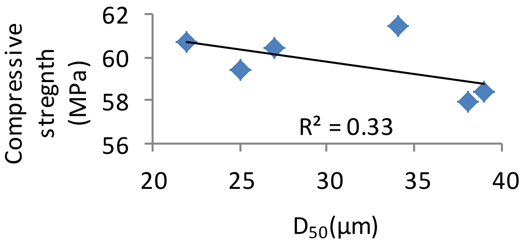


Figure 12 Fineness vs 14 day compressive strength PFA20

Figure 13 Fineness vs 28 day compressive strength PFA20

PFA30

Figures 14-17 show the correlation between SiO_2/fineness and 14/28 days compressive strength for 30% PFA replacement. The results show that compressive strength at 14 and 28 days, the SiO_2 had regression values of 0.48 and 0.7 respectively and for the fineness it was 0.78 and 0.55 respectively. The results show that at 14 days the fineness has greater influence than SiO_2 and this is believed to be due to the finer particles increasing the surface area. At 28 days the SiO_2 content had greater correlation with strength however the fineness still had greater correlation than at 10% and 20% replacement. Fineness influences strength because the finer the particles provide greater reactivity [19] and at 28 days it can be assumed that the PFA content has a significant effect on strength as both fineness and SiO_2 content have correlations with the strength.

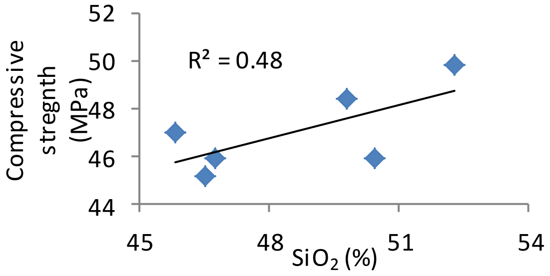


Figure 14 SiO_2 vs 14 day compressive strength PFA30

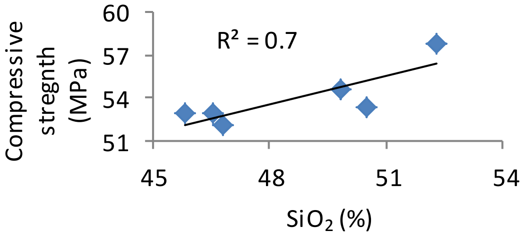


Figure 15 SiO_2 vs 28 day compressive strength PFA30

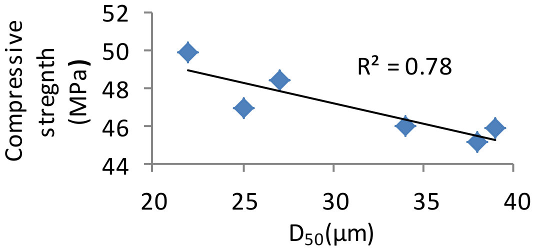


Figure 16 Fineness vs 14 day compressive strength PFA30

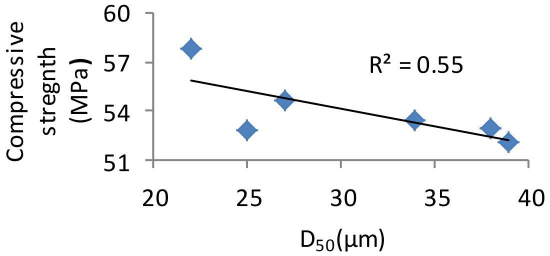


Figure 17 Fineness vs 28 day compressive strength PFA30

BPD5

Figures 18-21 show the correlation between fineness/SiO_2 + CaO and 14/28 days compressive strength for 5% BPD replacement. The results show that at 14 and 28 days the strength of the paste was dependent on the fineness of the material. Figures 18 and 19 show that as time increased from 14 to 28 days the correlation increased from 0.8 to 0.88, respectively. CaO and SiO_2 are the two predominant oxides within BPD and during hydration it is assumed that these oxides are the predominant reason for strength increase through the production of CSH [16]. When analysing the correlation between chemical properties and strength there was no significant correlation between the two, as correlation values were 0.1 for 14 and 28 days. The low impact of CaO and SiO_2 content is assumed to be due to the large differences within the particle distribution, which results in mixes containing finer particles providing a more intense reaction and denser hydrated structures [20] and hence greater strengths. The effect of chemical composition can be seen when comparing samples obtained in July and December/ September and November as they have very similar particle distribution values. For July and December the $CaO+SiO_2$ content was 56.82% and 69.68%, respectively and for September and November it was 62.28% and 66.09%, respectively. In both comparisons it was noted that the greater content of $CaO+SiO_2$ resulted in a greater strength being achieved.

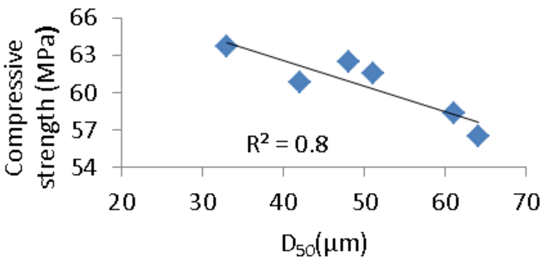


Figure 18 Fineness vs 14 day compressive strength BPD5

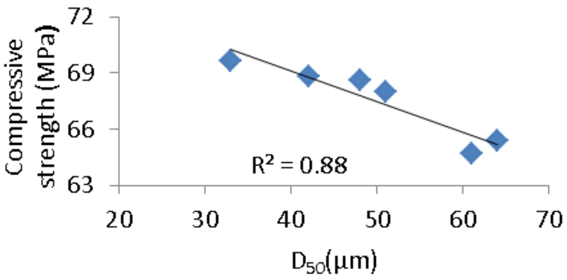
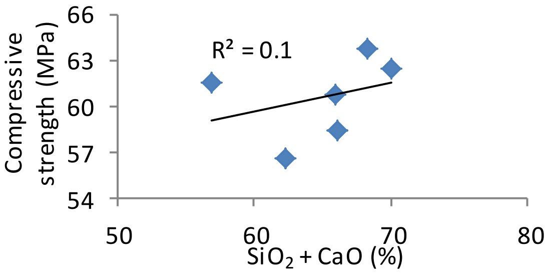


Figure 19 Fineness vs 28 day compressive strength BPD5



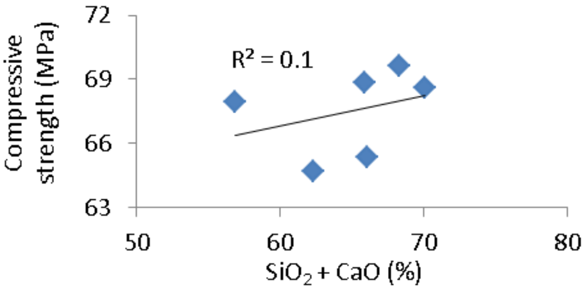
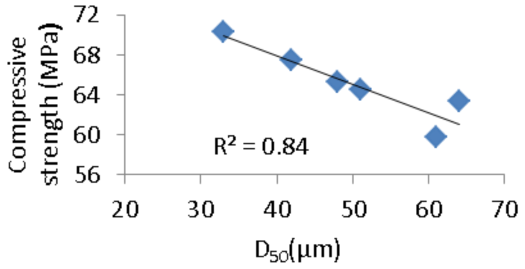


Figure 20 SiO_2 +CaO vs 14 day compressive strength BPD5

Figure 21 SiO_2 +CaO vs 28 day compressive strength BPD5

BPD10

Figures 22-25 show the correlation between fineness/SiO_2 + CaO and 14/28 days compressive strength for 10% BPD replacement. In comparison to 5% replacement, 10% replacement showed an increase in the regression values for fineness and SiO_2 +CaO. The correlation between fineness and compressive strength for 14 and 28 days was 0.84 and 0.88, respectively and as noted in BPD5 the fineness of the material seemed to dictate the strength achieved. The increase in fineness results in decreased strength. The correlation between SiO_2 +CaO and strength at 14 and 28 days was 0.19 and 0.32, respectively. Although at 10% replacement the oxide content seem to gain greater importance in strength development than at 5% the regression values were still low. When comparing the July and December/ September and November samples which had similar particle distribution values the same trend as noted in 5% replacement was noted, in which the samples with greater SiO_2 + CaO content produced greater results.



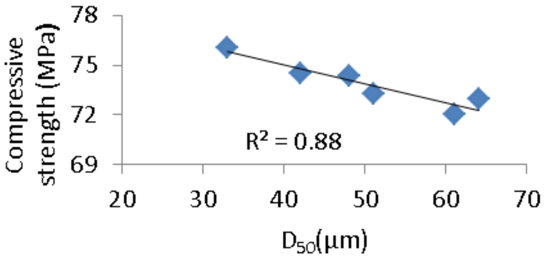
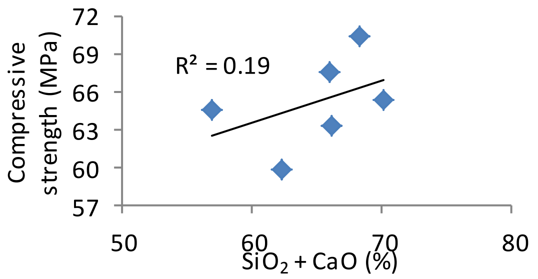


Figure 22 Fineness vs 14 day compressive strength BPD10

Figure 23 Fineness vs 28 day compressive strength BPD10



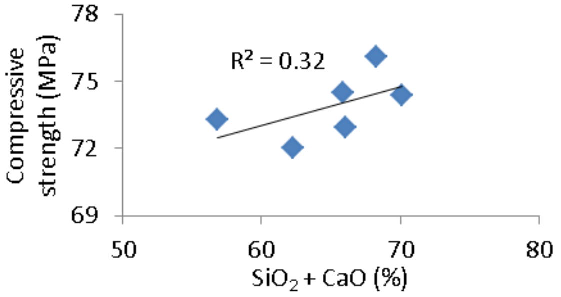


Figure 24 SiO_2 +CaO vs 14 day compressive strength BPD10

Figure 25 SiO_2 +CaO vs 28 day compressive strength BPD10

5. Conclusion

The aim of this research was to see the variation in chemical and physical properties of material obtained on a monthly basis over a period of 6 months and to analyse the effect of this on the compressive strength in semi-dry cement paste and the following conclusions were drawn.

- The addition of BPD in PFA-OPC blends did not results in greater strengths and this is assumed to be due to the high SO_3 content.

- For both PFA and BPD the chemical composition of the major oxides had similar variability's over the 6 months being analysed, however the particle size distribution was much more variable for BPD than PFA.
- As PFA levels increased in replacement, the fineness of the material played a greater role in strength development, in every sample apart from the November sample at 10% and 20% replacement. The results showed that at 14 days the fineness had greater impact on strength and at 28 days the SiO_2 content had greater impact on strength.
- The high variability in BPD particle size distribution played a major role in the strength development at both 5% and 10% replacement. The samples with finer particles produced the greatest strength and this is believed to be due to particle packing as well as finer particles having greater reactivity.
- PFA and BPD varied from the same source over a period of 6 months on a monthly basis and this variability affected the strength that was achieved. If industry was to implement the use of such materials then it is recommended that the materials chemical composition and to a much greater extent the particle size distribution is regulated in order to get a suitable range for which industry could make predicted strengths.

Reference:

[1] Joshi, R. C. -. L., R.P. (1997). *Fly Ash in Concrete; Production,Properties and Uses.* Overseas Publishers Association, Amsterdam, The Netherlands.

[2] Canpolat F, Yılmaz K, Köse MM, Sümer M, Yurdusev MA. (2004) "Use of zeolite, coal bottom ash and fly ash as replacement materials in cement production". Cem Concr Res 34, 731-735.

[3] Ganjian, E, Sadeghi- Pouya, H, Claisse, P, Waddell, M, Hemmings, S, and Johansson, S. (2008), "Plasterboard and gypsum waste in a novel cementitious binder for road construction", *Concrete Magazine of concrete society,* 42 (6), 20-22.

[4] Li, G., and Wu, X. (2005). "Influence of fly ash and its mean particle size on certain engineering properties of cement composite mortars." *Cem.Concr.Res.,* 35(6), 1128-1134.

[5] Lachemi, M., Hossain, K. M. A., Shehata, M., and Thaha, W. (2008). "Controlled low strength materials incorporating cement kiln dust from various sources." *Cem Concr Comp,* 30(5), 381-392.

[6] BSI (British Standard Institute), BS EN197-1: Cement, part 1: composition, specifications and conformity criteria for common cement, London, UK, 2011

[7] Cemex, 2009. *Material safety datasheet: Flue dust Portland Cement.* Rugby: Cemex UK Operations Ltd.

[8] Hanson, 2009. *Health and Safety data sheet for Common Cements and Cement Products,* Stamford: Hanson Heidelberg Cement Group.

[9] British Standards Institution, Specification for pulverized-fuel ash for use with Portland cement, BS 3892: Part 1, 1993

[10] Ganjian E, Jalull G, Sadeghi-Pouya H. (2015). "Using waste materials and by-products to produce concrete paving blocks". *Constr Build Mater.,*77(0)*,* 270-275*.*

[11] Papadakis, V. G. (1999). "Effect of fly ash on Portland cement systems: Part I. Low-calcium fly ash." *Cem.Concr.Res.,* 29(11), 1727-1736.

[12] Uygunoğlu, T., Topcu, I. B., Gencel, O., and Brostow, W. (2012). "The effect of fly ash content and types of aggregates on the properties of pre-fabricated concrete interlocking blocks (PCIBs)." *Constr.Build.Mater.,* 30(0), 180-187.

[13] Siddique, R., Kapoor, K., Kadri, E., and Bennacer, R. (2012). "Effect of polyester fibres on the compressive strength and abrasion resistance of HVFA concrete." *Constr.Build.Mater.,* 29(0), 270-278.

[14] Siddique, R. (2006). "Utilization of cement kiln dust (CKD) in cement mortar and concrete—an overview." *Resour.Conserv.Recycling,* 48(4), 315-338.

[15] Maslehuddin, M., Al-Amoudi, O. S. B., Rahman, M. K., Ali, M. R., and Barry, M. S. (2009). "Properties of cement kiln dust concrete." *Constr.Build.Mater.,* 23(6), 2357-2361.

[16] Najim, K. B., Mahmod, Z. S., and Atea, A. M. (2014). "Experimental investigation on using Cement Kiln Dust (CKD) as a cement replacement material in producing modified cement mortar." *Constr.Build.Mater.,* 55(0), 5-12.

[17] Barbhuiya, S. A., Gbagbo, J. K., Russell, M. I., and Basheer, P. A. M. (2009). "Properties of fly ash concrete modified with hydrated lime and silica fume." *Constr.Build.Mater.,* 23(10), 3233-3239.

[18] Wongkeo, W., Thongsanitgarn, P., Ngamjarurojana, A., and Chaipanich, A. (2014). "Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume." *Mater Des,* 64(0), 261-269.

[19] Chindaprasirt P, Jaturapitakkul C, Sinsiri T. (2005).” Effect of fly ash fineness on compressive strength and pore size of blended cement paste”. *Cem Concr Comp.*, 27(4), 425-428.

[20] El-Mohsen MA, Anwar AM, Adam IA. (2015).”Mechanical properties of Self-Consolidating Concrete incorporating Cement Kiln Dust”. *HBRC Journal,* 11(1), 1-6.

Acknowledgements

The authors gratefully appreciate and acknowledge the financial support from the 2 Engineering and Physical Sciences Research Council and Hanson Formpave who have 3 sponsored the PhD programme. The authors also acknowledge the support and facilities that 4 were provided at Coventry University.