Engineering Journal issn: 0125-8281

Article

Effects of Pulverized Burnt Clay Waste Fineness on the Compressive Strength and Durability Properties of Concrete

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Abstract. In this study, the fineness of pulverized burnt clay waste (PBCW) was evaluated as a factor that affects the compressive strength, resistance to chloride penetration and acid attack on concrete. PBCW obtained from a source was divided into two different fineness portions using 75 and 150 μm sieves and classified as a fine and coarse portion, respectively. Portland cement was replaced at 0 (control), 10 and 20% by weight with fine and coarse portions separately. Additional mix containing 105% binder content consisting of 5% excess fine and coarse portions were included in the 10 and 20% cement replacement. Chloride penetration was measured using full immersion technique in 3% sodium chloride solution while percentage mass loss and strength deterioration were assessed using a 5% sulphuric acid solution. Incorporating PBCW in concrete increases the demand for superplasticiser at a constant water-cement ratio but more prominent with the fine PBCW. The use of fine PBCW resulted in a significant improvement in compressive strength, chloride ion penetration and strength deterioration of the concrete. The fine PBCW is suggested to be more reactive due to the increased specific surface area resulting from its particles been obtained from a smaller sieve size than the coarse PBCW. Concretes containing PBCW performed better in mass loss reduction than control specimens in the aggressive medium. The PBCW cement concrete properties were further improved with the use of 105% total binder content containing 5% excess pozzolan, especially at 10% cement replacement.

Keywords: Pulverized burnt clay waste, chloride penetration, strength deterioration, compressive strength, mass loss, effect of fineness.

ENGINEERING JOURNAL Volume 22 Issue 2
Received 3 July 2017
Accepted 7 February 2018
Published 30 March 2018
Online at http://www.engj.org/
DOI:10.4186/ej.2018.22.2.83

DOI:10.4186/ej.2018.22.2.83

1. Introduction

Compressive strength is one of concrete's most important property and a major criterion of quality in structural design. In the past, the neglect of quality and lifecycle management of concrete has been observed to be responsible for the deterioration of concrete structures with emphasis given to the mechanical properties and structural capacity [1]. The durability of concrete is important to increase the service life of structures. Thus, strength and durability of concrete are important in defining structural concrete quality. Two of the most important aspects of the durability of concrete are the resistance to chloride penetration [2] and sulphuric acidic attacks [3]. Chloride ions attack on concrete is described as a specific and unique destroyer of concrete structures, which results in the corrosion of reinforcements embedded in concrete [4]. On the other hand, sulphuric acid attack on a concrete structure results in a severe deterioration of concrete due to its ability to consume calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), calcium hydroxide, and monosulphate, which are compounds of cement hydration [5].

Although cement is a vital material in the construction industry, its increasing demand, intense raw material utilisation, cost, energy consumption, greenhouse effect and durability consideration of concrete structures have all resulted in the search for alternative materials that could act as supplementary cementitious materials, otherwise known as pozzolanic materials. The durability of a concrete structure is strongly dependent on its material transport properties such as permeability, sorptivity, and diffusivity [6]. These material transport properties are improved by incorporating pozzolans from natural, industrial and agricultural wastes, which bring about refinement in the porosity and pore size distribution of the cement paste [7]. Pulverized burnt clay waste (PBCW) has been used in the past as a pozzolan and its incorporation, as discussed by researchers [8-12], helps to improve the engineering properties of concrete and mortar. It improves the material transport properties, which makes the concrete and mortar less susceptible to chloride and other chemical attacks.

With the exception of silica fume, which has a high natural fineness, low early age compressive strength of blended cement concrete has been a major concern when incorporating pozzolans in concrete. Blended cement concrete depends on later ages for strength development. The low early compressive strength does not favour reinforced concrete works where concrete structures are expected to have gained sufficient strength at 28 days water curing. From literature, it has been stated that the total specific surface area (SSA) of cement represents the material available for hydration [13]. Thus, the fineness of the particles of the binder determines the rate of hydration, which invariably influences durability performance of blended cement concrete. The fineness of pozzolans has a strong influence on the properties of blended cement concrete. Past studies especially on fly ash [2-4] have shown that increasing the specific surface area (SSA), which corresponds to increase in the fineness of pozzolan, have a packing effect and the ability to fill up small voids left by mixing water during evaporation, hence refining the concrete pore structure. This increased fineness goes to improve the early age strength development and likewise the durability properties of blended concrete.

However, research works on PBCW have not investigated the effects of PBCW fineness on compressive strength and durability properties of blended cement concrete. Olusola and Kolawole [11] and Kolawole *et al.* [12] considered PBCW particles passing through a 150 μm sieve. The result of their investigation revealed a low early-age compressive strength development. Kolawole *et al.* [12] tested the compressive strength of bamboo leaf ash (BLA), and PBCW blended cement concrete and found out that the incorporation of this pozzolans resulted in a decrease in the strength especially at an early age. However, at later ages, the compressive strength improved. The research, however, did not emphasise the fineness of the pozzolans which could improve strength possibly even at an early age.

In a durability investigation of a ternary combination of ordinary Portland cement (OPC), BLA and PBCW blended cement concrete in sulphuric acid [11], it was observed that incorporating BLA and PBCW in concrete improves resistance to compressive strength deterioration in sulphuric acid. Likewise, research on waste ceramic tile [8, 10] which is related to the material obtained from burning clay, has been carried out to improve concrete properties. With significant improvement in durability properties of burnt clay materials, the role of fineness as a factor that influences strength development has not been well established by considering a varying range of fineness as carried out in pozzolan like fly ash. Chindaprasirt *et al.* [3] found out that even in a severe 5% sulphuric acid concentration, mass loss due to the acidic attack on cement hydration product can be reduced with the incorporation of fly ash irrespective of the fineness, especially with the coarse fly ash resulting in the optimum performance. Chindaprasirt *et al.* [3] attributed the lowest rate of mass loss by the coarse fly ash to the better bonding of its particles to the cement matrix and less hydration product. Roy *et al.* [14] also tested the resistance to weight loss of silica fume, metakaolin and low-calcium fly ash blended cement concrete in an adverse sulphuric acidic environment (5% sulphuric acid concentration) and observed improved performance with pozzolans incorporation.

In a research on the influence of fly ash fineness on the chloride penetration of concrete [2], chloride resistance of concrete was evaluated using the rapid chloride permeability test of ASTM C1202 and also chloride ingress using both full and partial immersion methods. The finding showed that all three test methods carried out showed a similar pattern of improved resistance to chloride penetration with the incorporation of fly ash and with an increase in the fly ash fineness. Based on the similarities in the results from either of the test methods, the full immersion technique was employed in this study. Fineness, therefore, plays an essential role in defining concrete strength and durability performance.

It is therefore vital to understand how the fineness of PBCW influences the compressive strength, chloride penetration and sulphuric acid resistance of blended cement concrete. For this study, two fineness portions of PBCW were selected, categorised as fine and coarse portions, which were obtained from particles passing through 75 and 150 μm sieves, respectively. It is acknowledged that a similar study using fly ash made use of three broad fineness categories: fine, medium and coarse portions, with results showing optimum performance with the medium portion, which lies between the two extremes of the fine and coarse. However, due to cost and energy conservation in grinding further the burnt clay waste, only the fine and coarse portions of PBCW were utilised in this research.

This study on the use of PBCW with different fineness to improve early-age compressive strength, chloride penetration and sulphate resistance is, therefore, essential in providing relevant information that will aid the application of PBCW in concrete production.

2. Research Significance

PBCW has been established as a supplementary cementitious material for concrete production [8, 9], although, like other pozzolanic materials, strength development in the early ages is slow. Increasing the fineness of pozzolanic materials can increase its reactivity, hence the strength and durability performance of the blended cement concrete. The effect of fineness of PBCW on the strength and durability performance of PBCW blended cement concrete has been investigated and reported. Furthermore, researchers have established an optimum replacement level of OPC with PBCW as 10% by weight [11, 12]. Aside from the mix compositions containing 0, 10 and 20% OPC replacement with fine (F) and coarse (C) PBCW portions, four additional mixes were included for investigation. The four additional mixes had a total binder content of 105%, constituting 90% OPC + 15% F, 90% OPC + 15% C, 80% OPC + 25% F and 80% OPC + 25% C. Therefore, a total of nine mixes were used in this study.

3. Materials and Methods

3.1. Materials

Burnt clay brick obtained from a demolished building in Osun State, Nigeria was pulverized in a milling machine and used as PBCW. Two PBCW fineness classified as F and C portions were obtained by sieving the milled burnt clay brick into two sizes of 0-75 μm and > 75-150 μm, respectively. From the chemical composition of the OPC and PBCW presented in Table 1, and also that of the blended cement in Table 2, there were no significant changes in the values obtained between the elemental oxide of the F and C portion PBCW as shown in Table 1. Similar mixes containing F and C portions of the blended cement in Table 2 were also not significantly different as expected. Hence, it can be said that the classification of PBCW into different fineness portion through sieving does not change its chemical composition since it is a physical process. The PBCW used is classified as a Class N pozzolan in accordance with ASTM C 618-08 [15] categorisation.

The consistency of cement and pozzolan is measured using the Vicat apparatus in accordance with BS EN 196-3 [16]. Being a clay material, the PBCW has a high affinity for water to form a sticky paste. The consistency of OPC, F and C PBCW are 28, 56 and 50%, respectively. The greater the water content of a paste of standard consistency, the finer the cementitious material [13]. This implies that the water content of a paste required for standard consistency is greater with finer PBCW. Type I Portland cement meeting the requirements of BS EN 197-1 [17] was used.

The specific gravity of cement is higher than fine PBCW while that of the fine PBCW is higher than coarse PBCW (3.14, 1.83, and 1.71, respectively). The lower values obtained for the specific gravity of the fine PBCW and coarse PBCW implies that large quantity of fine PBCW and coarse PBCW will be required. Locally obtained 20 mm maximum crushed granite with a specific gravity of 2.8 was used as coarse aggregate while river sand passing through 4.75 mm sieve with fineness modulus of 2.45 and specific gravity of 2.63 was used as the fine aggregate. Clean water was used for mixing the dry samples while Type F superplasticiser (SP) classified according to ASTM C494 [18] was used to adjust the rheology of the mix.

Table 1. Chemical composition and physical properties of OPC and PBCW.

Elemental Oxide (%)	**OPC**	**PBCW**	
		F	**C**
SiO_2	16.82	52.18	52.17
Al_2O_3	4.35	27.84	27.86
Fe_2O_3	2.43	13.06	13.05
CaO	60.39	0.73	0.71
MgO	1.43	0.51	0.52
SO_3	1.64	0.00	0.01
K_2O	0.16	0.14	0.13
Na_2O	0.02	0.00	0.00
LOI	9.84	1.67	1.68
Fineness (% residue on 45 μm sieve)	29	32	34
(% residue on 90 μm sieve)	3.94	0	3.93
Consistency (%)	28	56	50
Specific gravity	3.14	1.83	1.71

Table 2. Chemical composition and physical properties of blended cements in comparison to PC.

Elemental Oxide (%)	OPC	10F/90 OPC	15F/90 OPC	10C/90 OPC	15C/90 OPC	20F/80 OPC	25F/80 OPC	20C/80 OPC	25C/80 OPC
SiO_2	16.82	20.55	21.9	20.54	21.88	23.89	25.18	22.12	25.13
Al_2O_3	4.35	6.82	7.84	6.82	7.83	9.27	9.88	9.3	9.84
Fe_2O_3	2.43	3.33	3.8	3.31	3.77	4.37	4.7	4.37	4.72
CaO	60.39	54.65	52.44	54.77	52.41	48.8	47.1	48.86	47.07
MgO	1.43	1.3	1.26	1.31	1.28	1.22	1.19	1.2	1.2
SO_3	1.64	1.7	1.65	1.72	1.67	1.55	1.51	1.58	1.52
K_2O	0.16	0.18	0.18	0.17	0.18	0.34	0.39	0.33	0.38
Na_2O	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.05
LOI	9.84	8.25	7.97	8.2	7.92	7.39	7.24	7.4	7.2
Consist. (%)	28	29	29	29	29	29	30	29	29
Specific gravity	3.14	2.47	2.70	2.36	2.61	2.34	2.52	2.27	2.41
Fineness % residue on sieve:									
45 μm	29	30	30	31	31	32	32	32	32
90 μm	3.94	3.37	3.26	3.80	3.74	3.36	3.13	3.73	3.99

3.2. Mixing Details

In this study, OPC was replaced with F and C portions of PBCW separately at 0% (control), 10% and 20%. Batching of materials was done by weight. Aside from the replacement of OPC with F and C PBCW at 0, 10 and 20% for a total binder content of 100% (OPC + PBCW), additional mix proportion containing 105% binder content was also studied. The extra 5% F and C contents of PBCW were used to assess the possibility of offsetting the slow reactivity of the pozzolan with an efficiency factor of 5%. The idea of increasing the F and C contents of PBCW might serve as an improvement to the blended cement concrete properties through the pozzolan filling up more voids in the pore structure of concrete during hydration. This means that at 90% OPC content, four mixes will be formed containing 10% F, 15% F, 10% C and 15% C portions. At 80% OPC content, four other mixes containing 20% F, 25% F, 20% C and 25% C portions were also produced. Hence, nine different mixture compositions including the control (at 100% OPC) were tested in this research. At a constant water-to-binder (w/b) ratio of 0.5 adopted for all nine mixes, SP was used to maintain a slump of 75 ± 25 mm. After mixing of the constituent concrete materials, slump tests were carried out to determine the workability of each mix in accordance with BS EN 12350-2 [19]. The mix composition of the concrete samples including their slumps is shown in Table 3.

Table 3. Mix composition of concrete.

Mix	Composition (kg/m^3)							Slump (mm)
	OPC	F	C	Sand	Granite	Water	SP	
PCC	375	0.0	0.0	950	1300	187.5	1.5	55
10F/90OPC	337.5	37.5	0.0	950	1300	187.5	2.4	55
15F/90OPC	337.5	56.3	0.0	950	1300	196.9	3.3	55
10C/90OPC	337.5	0.0	37.5	950	1300	187.5	1.8	55
15C/90OPC	337.5	0.0	56.3	950	1300	196.9	3.2	55
20F/80OPC	300	75.0	0.0	950	1300	187.5	10.4	60
25F/80OPC	300	93.8	0.0	950	1300	196.9	11.3	65
20C/80OPC	300	0.0	75.0	950	1300	187.5	10.1	65
25C/80OPC	300	0.0	93.8	950	1300	196.9	11.0	65

3.3. Compressive Strength Test

Compressive strength test was carried out at the age of 7, 28 and 90 days using 100 mm cube samples cured in water in accordance with the BS EN 12390-4 [20]. The reported compressive strength test result is an average of three tests samples. A total of 81 samples were used in carrying out this test.

3.4. Chloride Penetration Tests using the Full Immersion Technique

This study adopted the experimental procedure for determining the chloride penetration of concrete described in the RTA T362 [21]. Although RTA T362 is one of the tests for sorptivity, it is also used to measure the depth of penetrating waterfront into concrete and a reasonable performance indicator of chloride resistance of concrete. The chloride penetration fronts of the concrete specimens immersed fully in 3% NaCl solution was determined using 0.1 mol/L silver nitrate as an indicator [22]. For this test, 100 mm diameter by 200 mm height cylinder samples was cured in water for 26 days. After the 26 days water curing, the samples were cut into four equal 50 mm slices with the 50 mm top and bottom ends of the cut cylinders discarded. Before the application of the epoxy coating, the cut cylinders were left to dry under laboratory condition for 24 hours. A total of 54 samples (50 mm slices) were used in carrying out this test.

For full immersion test, the epoxy coating was applied to the curve surface area and a top surface of the sliced samples. Only one circular top surface was coated for the full immersion test to allow penetration of chloride ion only in one direction. Afterwards, the coated samples were left in the laboratory for another day. At the age of 28 days (26 days curing in water + remaining 2 days for cutting, epoxy application and drying), the cut cylinders were fully immersed in 3% NaCl solution for a maximum period of 90 days. Test for chloride ion penetration in 3% NaCl solution was carried out at 30, 60 and 90 days. The penetration depth was an average of two 50 mm slices obtained from the one-cylinder sample. Figure 1 shows the test arrangement for evaluation of concrete resistance to chloride ion penetration under full immersion.

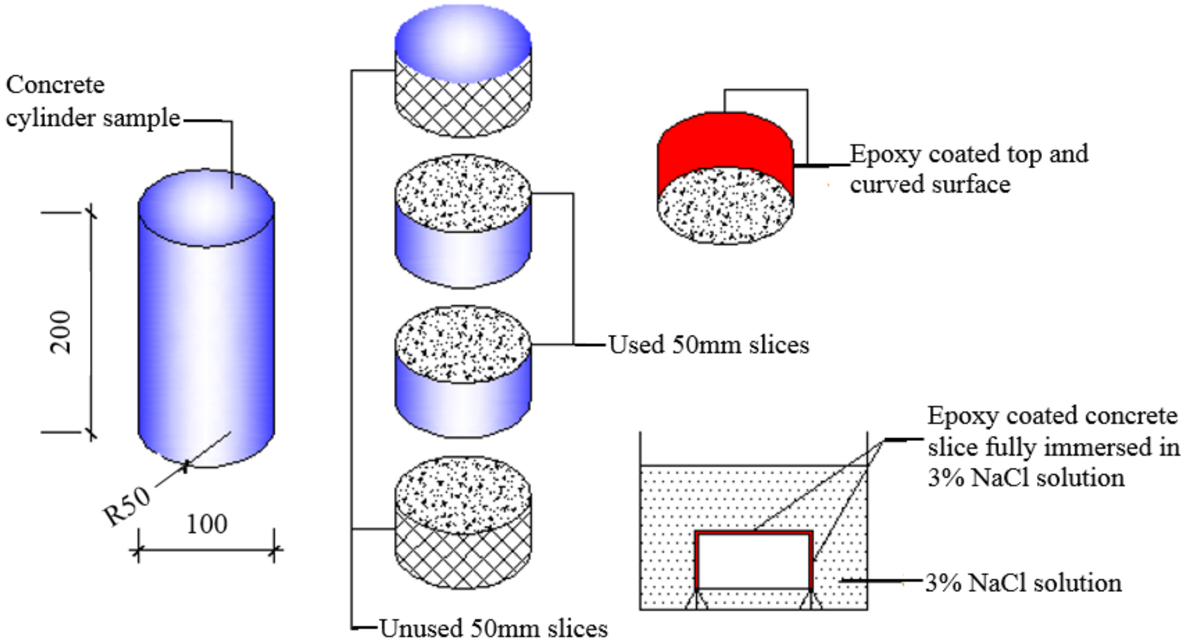

Fig. 1. Full immersion of concrete specimen in 3% NaCl solution [2].

3.5. Sulphuric Acid Attack Test

The sulphuric acid immersion test was carried out using 100 mm concrete cube samples cured in 0 (water) and 5% sulphuric acid (H_2SO_4), simulating a normal and a severe acidic environment, respectively. Samples were cured initially for 28 days in water before being transferred to 0 and 5% concentration of sulphuric acid solutions. A total of 162 samples were used to investigate the resistance to sulphuric acid attack.

Strength deterioration

Deterioration of the concrete samples in H_2SO_4 was investigated at 30, 60 and 90 days exposure periods using the strength deterioration factor (SDF) [11, 23] given in Eq. (1). The reported compressive strength was the average of three samples.

$$\text{SDF} = \frac{F_{cw} - F_{ca}}{F_{cw}} \times 100\% \tag{1}$$

where
F_{cw} = average compressive strength of concrete cube specimen in 0% (water); and
F_{ca} = average compressive strength of concrete cube specimen in 5% H_2SO_4 concentration

Mass loss

The mass loss of concrete cube specimens cured in acidic medium was also investigated. For each mix proportion, the mass was measured after exposure to 0 and 5% H_2SO_4 solution for periods of 30, 60 and 90 days after initial curing of the sample in water for 28 days. After that, the mass deterioration in percentage was calculated [3]. The mass loss was the average of three samples. The percentage mass loss was computed using Eq. (2).

$$\% \text{ mass loss} = \frac{M_1 - M_2}{M_2} \times 100\% \quad (2)$$

where M_1 is the mass of concrete cube specimen in 0% (water), and M_2 is the mass of concrete cube specimen in 5% H_2SO_4 solution.

4. Results and Discussion

4.1. Workability

Slump test was carried out for all wet mixtures to ascertain the workability of the blended cement concrete. The quantity of SP was adjusted as shown in Table 3 to achieve the desired slump (75±25 mm) for each mix,. Results showed that as the percentage of PC replacement increases and with excess F and C contents of PBCW, the quantity of SP to achieve the desired slump increases. This implies that in the absence of SP, the blended cement concrete becomes stiffer and less workable as the F or C contents of PBCW in the mix increases. Previous research on PBCW showed similar behaviour in the blended cement increase demand for water [12]. The high silica (SiO_2) content of the pozzolan (PBCW) as shown in Table 1 increases the silica content of the blended cement (Table 2), which will initiate a high demand for water required to achieve a fluid and desired workability of concrete [24]. This can also be attributed to the fact that PBCW been a clay product could absorb and retain more water to achieve the desired standard consistency of the blended cement as compared to the control without PBCW (Table 1). Furthermore, it was observed that increasing the fineness of PBCW as in the case of the mixture compositions containing the F of PBCW required more SP than their corresponding C. This is because of the increased SSA of fine pulverized burnt clay waste.

4.2. Compressive Strength

Table 4 reveals the compressive strength results carried out at 7, 28 and 90 days. From the results, the compressive strength increases with curing age for all the mix. At 7-day strength test, the control mixture (PCC) attained the highest strength of 16.3 MPa while those of the blended cement concrete had a strength ranging from 9.4 – 14.9 MPa. Mix 15F/90PC gave the highest strength among the blended cement concrete with a strength of 14.9 MPa and closely followed by mix 15C/90PC and 25F/80PC, both having the same strength of 14.1 MPa. Likewise, at 28-day strength test, the control mix (PCC) still gave the highest compressive strength of 27.0 MPa while those of the blended cement concrete had a strength ranging from 17.2 – 25 MPa. It can be said that at early ages of 7 and 28 days, the compressive strength of PBCW blended cement concrete results in a lower strength than control concrete (PCC). The lower strength attained by the PBCW blended cement conforms with previous researches on PBCW and other clay related pozzolans [8-12, 25, 26]. However, at 90-day strength test, mixes 10F/90PC (29.3 MPa) and 15F/90PC (29.9 MPa) attained strength greater than the PCC (28.5 MPa), while the rest of the blended cement concrete mixes were below the control (PCC). The low strength at an early age can be attributed to the fact that pozzolanic blended cement have higher activation energy and therefore results in a low rate of hydration (except silica fume), while at later ages, the compressive strength becomes higher [27, 28].

From the strength activity index (SAI) in Table 4, defined according to ASTM C 311 [29] as the ratio (in %) between the compressive strength of concrete containing substituting materials and that of the control at the same curing ages, it can be observed that as curing age increases, the SAI for all the replacement levels also increases. The SAI results at the 7-day for most of the mixes as presented in Table 4 were greater than 75%, conforming to ASTM C 618-08 [15], except for mix 20C/80PC (71%) and 25C/80PC (58.0%). At 28 days, the SAI for most of the mixes were greater than 75% conforming to ASTM C 618-08 [15] as also revealed in Table 4 except for mix 25C/80PC (64.0%). From the SAI obtained from the compressive strength test result, good strength development of the PBCW blended concrete is observed especially the fine PBCW concrete, which is dominant in comparison to that of the control concrete (PCC). Comparing mixtures containing fine PBCW (10F/90PC, 15F/90PC, 20F/80PC and 25F/80PC) and their corresponding coarse PBCW concrete (10C/90PC, 15C/90PC, 20C/80PC and 25C/80PC), it was observed that improving PBCW fineness increases the strength of the blended cement concrete. It can be explained that the increased strength resulting from the improved fineness was because of increased SSA associated with particles obtained from smaller sieve size of the fine PBCW resulting to highly dense and impermeable concrete [27, 30]. Similar to previous research on the fineness of cementitious materials, the fine PBCW have a packing effect that increases the density of concrete by reacting with calcium hydroxide during hydration to form more C-S-H that fills up small voids left by mixing water during evaporation [3, 31, 32]. This process of increasing densification by the fine PBCW is therefore responsible for the improved strength.

Table 4. Compressive strength of concrete.

Mix	Compressive strength (MPa – Strength activity index)		
	7 days	28 days	90 days
PCC	16.3 – 100	27.0 – 100	28.5 – 100
10F/90PC	13.7 – 84	23.1 – 86	29.3 – 103
15F/90PC	14.9 – 91	25.0 – 93	29.9 – 105
10C/90PC	13.4 – 82	22.4 – 83	26.1 – 92
15C/90PC	14.1 – 87	23.7 – 88	28.3 – 99
20F/80PC	12.2 – 75	21.4 – 79	24.3 – 85
25F/80PC	14.1 – 87	23.3 – 86	25.6 – 90
20C/80PC	11.6 – 71	20.3 – 75	23.1 – 81
25C/80PC	9.4 – 58	17.2 – 64	20.4 – 82

Furthermore, results presented in Table 4 reveal that mixes 15F/90PC, 15C/90PC and 25F/80PC containing excess increment of 5% in F and C contents at 10 and 20% PC replacement, attained strength greater than the conventional mixtures (10F/90PC, 10C/90PC and 20F/80PC, respectively) at all test ages. From Table 2, mixes 15F/90PC, 15C/90PC and 25F/80PC were found to be finer having lesser particle residue on the 90 μm sieves than their conventional mixes 10F/90PC, 10C/90PC and 20F/80PC, respectively. This implies that increasing the F and C contents of PBCW in the mixtures resulted in increased fineness of mixes 15F/90PC, 15C/90PC and 25F/80PC and increased the formation of C-S-H during the pozzolanic reaction. The improve fineness caused by the use of 5% excess F, and C portion can be explained to have possibly improved the pore structure and density of the concrete resulting in the further improved compressive strength. The only exception was mixture 25C/80PC with strength less than the conventional mix 20C/80PC at all ages. This can also be linked to the fineness result shown in Table 2, which showed that the percentage residue of particles on the 90 μm was less in the 20C/80PC (3.73%) than in the 25C/80PC (3.99%). This implies that the 20C/80PC blended cement had finer particles than the 25C/80PC. The presence of coarser particles of PBCW can be attributed to the decrease in strength of mix 25C/80PC. According to a research on fly ash [2], when the binder content of the fly ash concrete was increased with an efficiency factor there was an offset in the slower reaction of the fly ash resulting in improved strength and durability property. It can be inferred6 that an increment of PBCW content of the blended cement concrete causes more silicate in the pozzolan to react with calcium hydroxide formed during cement hydration leading to improved strength.

The 10% Portland cement replacement with PBCW mixes gave the optimum strength performance and can be concluded as the optimum replacement level which is also in conformity with previous research [11, 12, 26].

4.3. Chloride Penetration Depth

The result of the chloride penetration using the full immersion technique of cut cylinders in 3% NaCl solution and with 0.1 mol/L silver nitrate as an indicator is given in Fig. 2. The result shows that the chloride penetration increases with increasing exposure period in NaCl solution. However, the incorporation of PBCW decreases the penetration depth of chloride ion as compared with the control samples (PCC). Concrete interfacial transition zone (ITZ) is regarded as its weakest part and therefore requires important strategy that will stiffen and strengthen the ITZ to a level of discontinuity in interconnected pore [33]. The decrease in the rate of chloride ion penetration displayed by the PBCW blended cement concrete mixes as presented in Fig. 2 corresponds to reduce concrete permeability which makes PBCW useful in improving

ITZ of concrete. This means that the incorporation of PBCW decrease the average pore size of cement paste and could be an indication of improved ITZ of concrete, although not investigated in this research [33,34]. This could be achieved by the PBCW filling up of voids left by mixing water during evaporation resulting in improved resistance to penetration of chloride ions and later age strength from the secondary C-S-H. The filling up of the voids by the PBCW will then result in the refinement of the pore thereby causing discontinuity of interconnected pore leading to improvement in chloride resistance.

At 30 days exposure to chloride ion, mix 15F/90PC showed the optimum resistance to chloride ion penetration with a penetration depth of 7.5 mm while the control mix (PCC) was 9.5 mm. Mix 10F/90PC (8.0 mm) and 15C/90PC (9.0 mm) also showed better resistance to chloride ion penetration than the control, while mix 10C/90PC and 25F/80PC had the same penetration depth of 9.5 mm with the control. Similar pattern in chloride ion penetration resistance was observed at 60 and 90 days exposure periods with most of the blended cement concrete mix having better resistance to chloride penetration than the control mix except for mix 20C/80PC and 25C/80PC. It was observed that the resistance to chloride penetration was better improved with an increase in the fineness of PBCW as observed with the fine PBCW mixes (10F/90PC, 15F/90PC, 20F/80PC and 25F/80PC). Similar to the compressive strength results shown in Table 4, the reason for the improved resistance by mixtures containing fine PBCW (10F/90PC, 15F/90PC, 20F/80PC and 25F/80PC) relative to the mixes containing coarse PBCW (10C/90PC, 15C/90PC, 20C/80PC and 25C/80PC) can be attributed to increased SSA of the fine PBCW. It is suggested that during the pozzolanic reaction, the F have a higher SSA than the C and therefore possess a better reaction ability with calcium hydroxide to form CHS that fill up small voids left by mixing water during evaporation. Increasing fineness, therefore, causes refinement in the porosity and pore size distribution of the concrete reducing its permeability, thereby resulting in a reduction in chloride penetration [2].

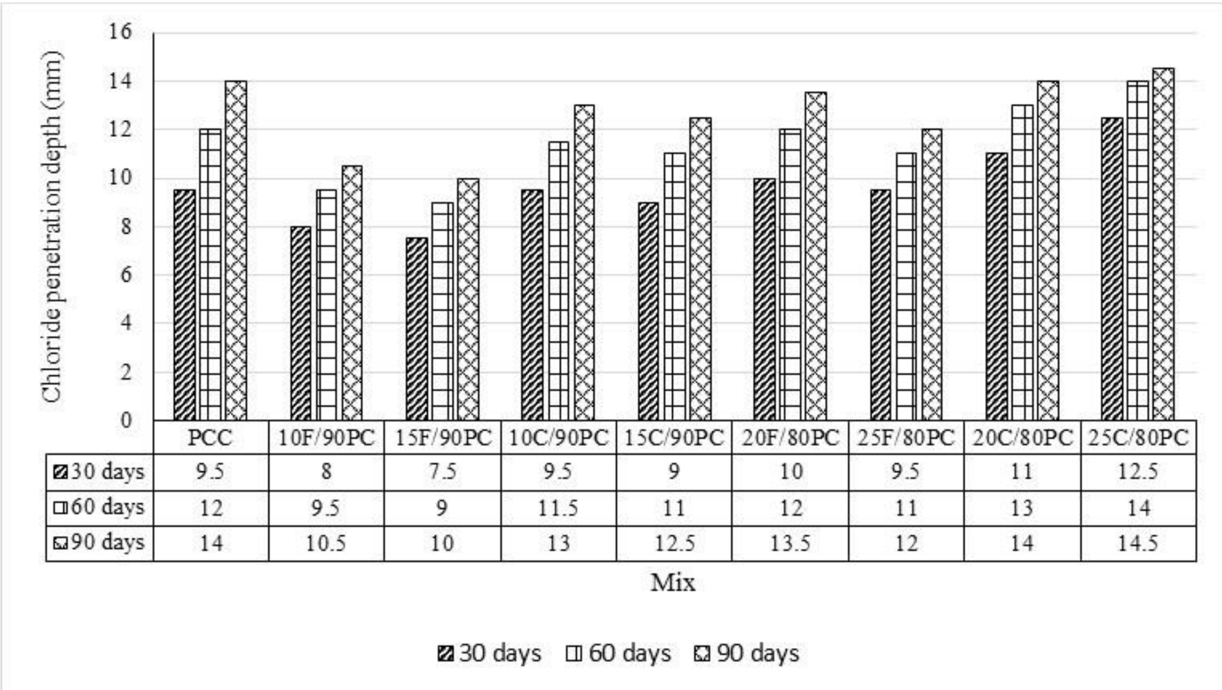

Fig. 2. Chloride penetration depth of full immersion in 3% NaCl solution.

Similarly, with reference made to the compressive strength result in Table 4, the findings of Fig. 2 reveals that mixtures 15F/90PC, 15C/90PC and 25F/80PC containing excess increment of 5% in F and C contents at 10 and 20% PC replacement, further reduce chloride penetration than the conventional mixtures (10F/90PC, 10C/90PC and 20F/80PC, respectively) at all test ages. As stated under the section on the compressive strength, improved chloride penetration is due to improved fineness (less percentage residue in 90 μm) for the 5% PBCW excess mixes with an exception to mix 25C/80PC. Increasing the F and C content in the mix resulted in increased formation of C-S-H during the pozzolanic reaction. This could have resulted further in the discontinuity of interconnected pore through the filling up of voids left by mixing water during evaporation resulting in improved strength and resistance to penetration of chloride ions. As previously stated, the only exception was mix 25C/80PC with chloride penetration depth greater than the conventional mix 20C/80PC at all ages due to the presence of coarser particles in the 20C/80PC mix as presented in Table 2. The result shows that at all exposure period in chloride environment, mix 15F/90PC had the best performance which can also be seen in it high compressive strength in Table 4.

From both the strength and chloride penetration results, it can be inferred that the rate of chloride penetration in PBCW blended cement concrete is closely related to the compressive strength. In other words, as the strength increases with time for the blended concrete the rate of chloride penetration reduces simultaneously. Likewise, for the PBCW blended cement concrete, the higher the compressive strength, the lower the chloride penetration depth and vice versa. The inverse relationship between the chloride penetration and the compressive strength of the PBCW blended cement concrete excluding the control with PBCW can be seen in Fig. 3 showing the relation of the 90 days chloride penetration as against the 90 days compressive strength.

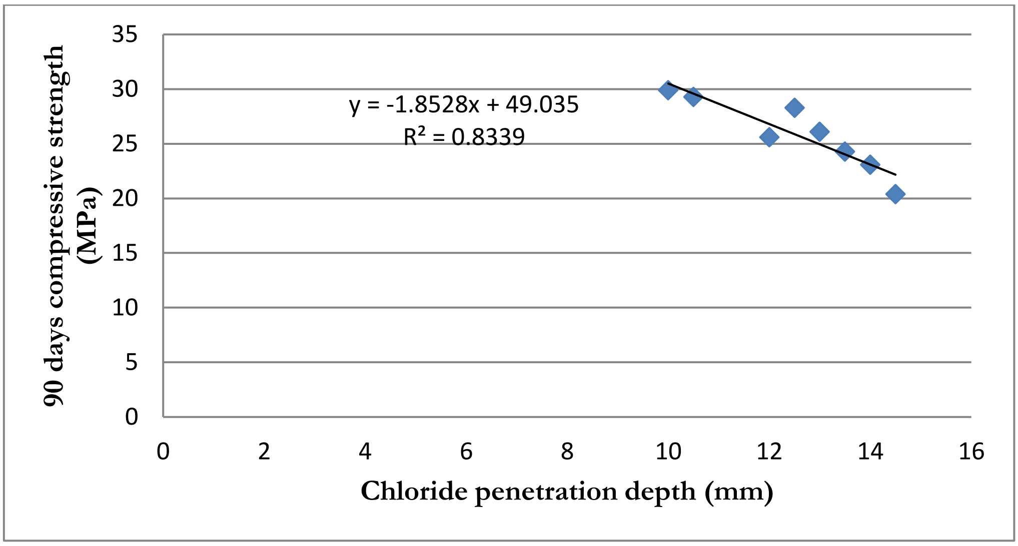

Fig. 3. Chloride penetration depth vs compressive strength at 90 days.

From the line of best fit shows in Fig. 3, a closed variation can be seen between the points with a coefficient of determination of 0.8339. This depicts that 83.39% of the compressive strength at 90 days is explained by the 90 days penetration depth for the PBCW blended cement concrete. Table 5 below shows the percentage deviation of the predicted compressive strength from the actual compressive using the equation on Fig. 3. Table 5 shows that the percentage deviation ranges between -8.57% and 8.67% which is quite close to the actual compressive strength. The closest prediction was mix 20C/80PC with a deviation of –0.02%.

Table 5. Deviation of predicted 90 days compressive strength from the actual 90 days compressive strength.

Mix containing PBCW	Chloride penetration depth at 90 days	Actual compressive strength (MPa)	Predicted compressive strength (MPa)	% Deviation
10F/90PC	10.5	29.3	29.58	0.96
15F/90PC	10	29.9	30.51	2.03
10C/90PC	13	26.1	24.95	-4.41
15C/90PC	12.5	28.3	25.88	-8.57
20F/80PC	13.5	24.3	24.02	-1.14
25F/80PC	12	25.6	26.80	4.69
20C/80PC	14	23.1	23.10	-0.02
25C/80PC	14.5	20.4	22.17	8.67

Although the test for chloride ion penetration was restricted to just the full immersion technique similar to the procedure in RTA T362 [21], the result obtained can be used to predict the behaviour of PBCW blended cement concrete in resisting electrical conductivity. As stated previously in the introduction, Chindaprasirt *et al.* [2] in a research to investigate resistance to chloride ion penetration of fly ash blended cement concrete carried out three different test procedures. The similarity in the trend of results obtained in the three tests can help to make an inference as to what the resistance to coulomb charge of PBCW blended concrete behaviour will be using the full immersion test. Therefore, from the full immersion test result in this research we could predict that the coulomb charge (assuming the rapid chloride permeability test according to ASTM C1202 was carried out) of PBCW blended cement concrete will decrease with the incorporation of PBCW and increased fineness of PBCW.

4.4. Resistance to Sulphuric Acid

Strength deterioration

The results of the compressive strength of the cube samples cure in 0% (water), and 5% sulphuric acid (H_2SO_4) are as presented in Table 6. For the control samples cured in 0% H_2SO_4, as expected, the compressive strength increases with exposure period. However, in 5% H_2SO_4, the result revealed significant deterioration in strength of cube samples for all the mix composition and deteriorated more with increased exposure period. The significant decrease in compressive strength reveals the aggressive behaviour of H_2SO_4 on concrete structures, which behaves both as an acid and as sulphate [35]. It aggressive behaviours consumes the calcium silicate hydrate, calcium aluminate hydrate, calcium hydroxide, and monosulphate, which are the compounds of cement hydration [5]. With increasing exposure period, H_2SO_4 continues to attack the CSH formed during cement hydration, which is majorly responsible for the strength of concrete. This leads to leaching away from the CSH resulting in increasing deterioration.

From the results in Table 5, the compressive strength in 5% H_2SO_4 is higher with the incorporation of PBCW as compared with the control mix (PCC). Similar compressive strength pattern can be observed at all 5% H_2SO_4 exposure periods as shown in Fig. 4 for all the mix with mix 20F/80PC showing the best performance at all curing ages except at 30 days where 15F/90PC was the highest. The control mix (PCC) in general revealed the least performance in sulphuric acid and could be inferred to mean that incorporation of PBCW improves the ITZ [33] of its blended concrete, hence improving resistance to sulphuric acid. Similar to the findings in the compressive strength results discussed above in Table 4, resistance to sulphuric acid attack can be improved with increased PBCW fineness. This can be seen with the F portion mix (10F/90PC, 15F/90PC, 20F/80PC and 25F/80PC) resulting to higher strength in 5% H_2SO_4 than their corresponding C portion mix (10C/90PC, 15C/90PC, 20C/80PC and 25C/80PC). The improved strength performance of the blended concrete can also be seen in the reduction of the strength deterioration factor (SDF) of the blended cement concrete as shown in Fig. 5.

Table 6. Compressive strength of cube samples in sulphuric acid.

Mix	Compressive strength (MPa)					
	30 days		60 days		90 days	
	0%	5%	0%	5%	0%	5%
PCC	28.0	14.5	28.5	10.1	28.7	7.7
10F/90PC	28.7	17.6	29.3	14.8	30.5	11.2
15F/90PC	29.4	19.1	29.9	15.4	30.9	13.0
10C/90PC	23.3	16.5	26.1	14.4	27.7	11.0
15C/90PC	27.2	17.0	28.3	15.2	29.7	12.4
20F/80PC	23.5	18.9	24.3	17.0	26.8	14.4
25F/80PC	24.8	15.3	25.6	13.3	27.3	11.6
20C/80PC	22.3	14.8	23.1	13.7	23.7	11.5
25C/80PC	19.4	13.4	20.4	12.6	21.3	10.3

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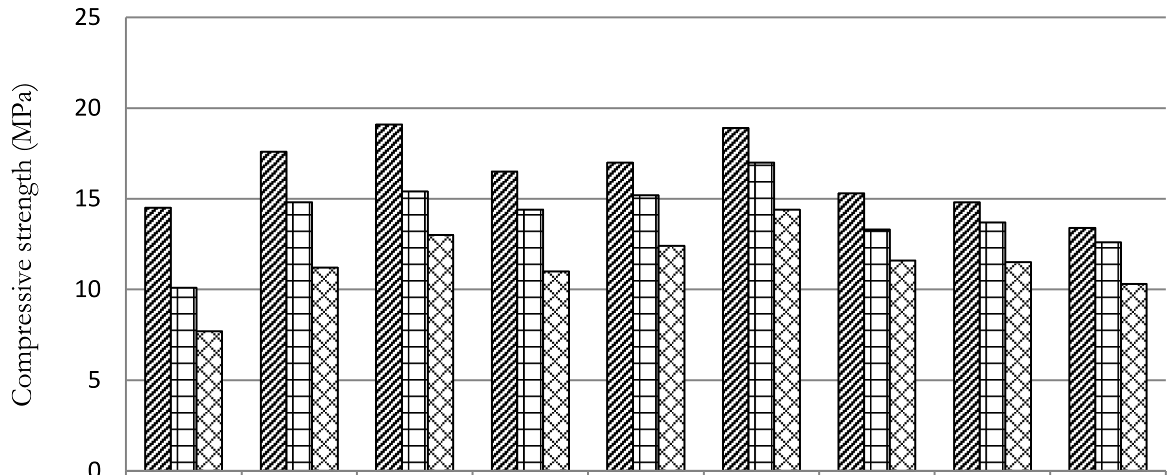
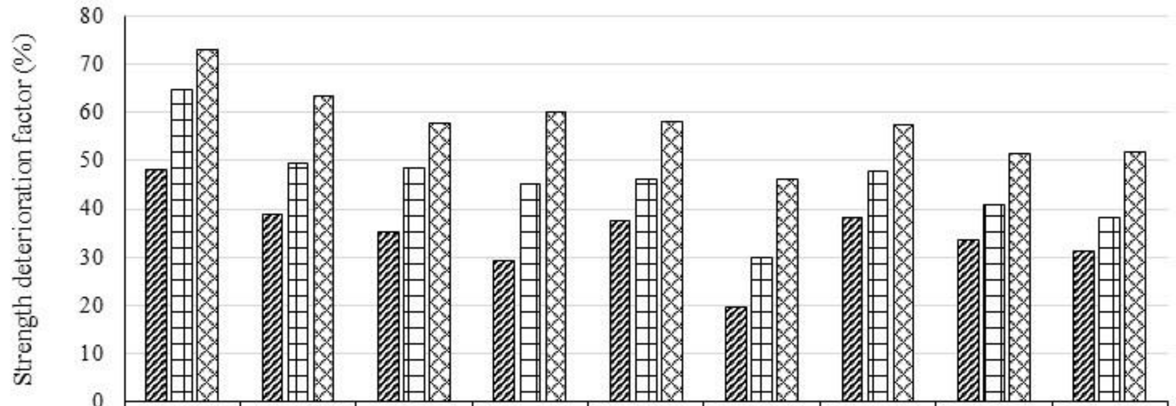


	PCC	10F/90PC	15F/90PC	10C/90PC	15C/90PC	20F/80PC	25F/80PC	20C/80PC	25C/80PC
30 days	14.5	17.6	19.1	16.5	17	18.9	15.3	14.8	13.4
60 days	10.1	14.8	15.4	14.4	15.2	17	13.3	13.7	12.6
90 days	7.7	11.2	13	11	12.4	14.4	11.6	11.5	10.3

Mix

Fig. 4. Compressive strength of cube samples in 5% sulphuric acid.



	PCC	10F/90PC	15F/90PC	10C/90PC	15C/90PC	20F/80PC	25F/80PC	20C/80PC	25C/80PC
30 days	48.2	38.7	35.1	29.1	37.4	19.7	38.3	33.6	31.2
60 days	64.6	49.5	48.4	45	46.3	30	47.9	40.7	38.3
90 days	73.1	63.3	57.8	60.1	58.1	46.2	57.4	51.5	51.9

Mix

30 days 60 days 90 days

Fig. 5. Strength deterioration factor of cube samples.

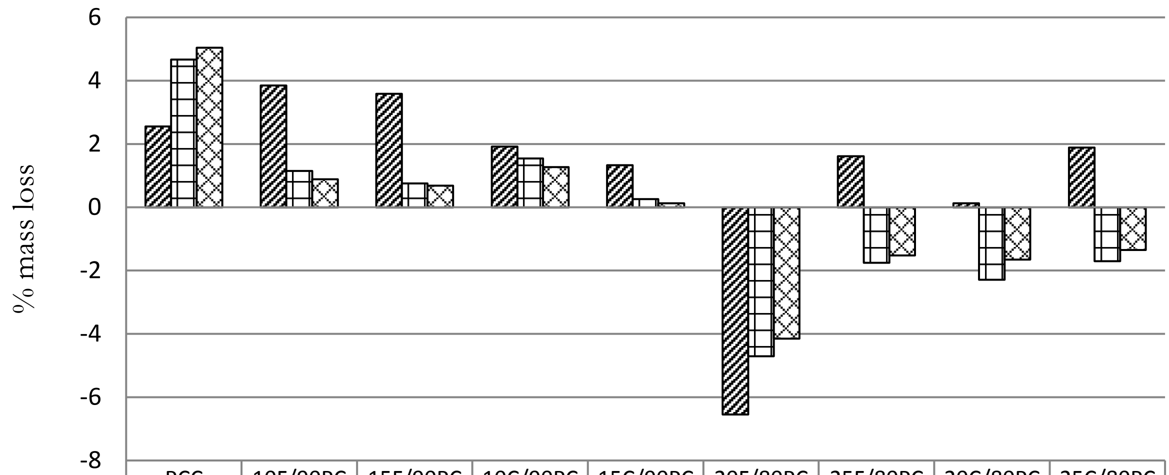
At all exposure periods, the control (PCC) gave the highest SDF of 48.2%, 64.6% and 73.1% at 30, 60 and 90 days respectively, with regards to the PBCW blended concrete and therefore implies that conventional concrete is strongly affected by sulphuric acid. It can be observed from Fig. 5 that mixture proportions containing 80% Portland cement (20F/80PC, 25F/80PC, 20C/80PC and 25C/80PC) mostly resulted in lower SDF even at 90 days exposure. This implies that increasing the percentage replacement of Portland cement with either F or C PBCW will result to improve resistance to strength deterioration in an acidic environment. PBCW as a pozzolan reacts with the calcium hydroxide form in concrete during hydration producing more CSH filling up the void in concrete, hence refining concrete pore structure. The refined pore structure of the blended cement concrete, therefore, reduced the aggressive attack of sulphuric acid. At 10% PC replacement, results show that mixtures containing 5% excess fine and coarse PBCW (15F/90PC and 15C/90PC, respectively) gave higher strength and reduced strength deterioration than their conventional mixes (10F/90PC and 10C/90PC, respectively). Similar to the findings from the compressive strength and chloride penetration, reduced strength deterioration of 15F/90PC and 15C/90PC can likewise be attributed to offsetting the slow pozzolan activity with the excess PBCW content.

Furthermore, it can be observed that the compressive strength results (Table 4) of mixtures containing the fine PBCW portions (10F/90PC, 15F/80PC, 20F/80PC and 25F/80PC) gives higher strength in 5% H_2SO_4 than their corresponding coarse PBCW mix (10C/90PC, 15C/80PC, 20C/80PC and 25C/80PC). Mix 20F/80PC gives the best acidic resistance (lowest SDF) at all exposure period and the highest compressive strength of 14.4 MPa at 90 days immersion in 5% H_2SO_4. This can be attributed to the improved fineness of the fine PBCW resulting for the increased SSA. This resulted in increased pozzolanic activity, with the resulting CSH filling up voids reducing interconnectivity of concrete pore and therefore less susceptible to sulphate attack [3].

Mass loss

The results of the percentage mass loss of the concrete samples subjected to 5% H_2SO_4 are as shown in Fig. 6. The rate of mass loss can be seen to have been improved with the incorporation of PBCW. Comparing the PBCW blended cement concrete samples with the control mix sample (PCC), the PCC mix gave the worst performance in a sulphuric acid environment with a continuous reduction in the mass of the samples at increased exposure period in sulphuric acid. From the physical appearance of samples from all the mixes, the PCC mix appeared to have experienced the most severe deterioration with the washing away of its constituent materials as seen in the Plates below (1-9). The sulphuric acid attack on each of the mixes also resulted in deterioration of the edges, corner and surface of the cube samples making them rough. It has been established that sulphuric acid attacks the CSH, CAH, calcium hydroxide, and monosulphate of concrete which are compounds of cement hydration [5]. The decrease in the rate of mass loss by the F and C mix results from the reaction of the PBCW present in the blended cement concrete with calcium hydroxide produced during cement hydration. The reaction process of PBCW with calcium hydroxide will result in the formation of secondary CSH and CAH, thereby reducing calcium hydroxide and consequently increasing the CSH and CAH useful in improving concrete properties. Mass deterioration was observed for most of the mixes at 30 days exposure in H_2SO_4 except for the 20C/80PC which had gained mass. At 60 and 90 days, exposure periods the sample mixes were observed to be deterioration almost at a constant rate. For mixes at 10% PC replacement (10F/90PC, 15F/90PC, 10C/90PC and 15C/90PC), it was observed that the rate of mass deterioration decreases with increasing exposure period in H_2SO_4. The C mixes (10C/90PC and 15C/90PC) gave lower deterioration than their corresponding F mixes (10F/90PC and 15F/90PC) which can also be seen in their different appearances in Plate 2-5. Incorporating excess F and C content in the mixes at 10% PC replacement (15F/90PC and 15C/90PC) cause further improvement in reducing mass deterioration than the convention 10% PC replacement mixes (10F/90PC and 10C/90PC). The behaviour for the mixes at 20% PC replacement (20F/80PC, 25F/80PC, 20C/80PC and 25C/80PC) was however different from the 10% PC replacement mixes in that the 20% PC replacement mixes gained mass at higher exposure periods of 60 and 90 days. Different also from the behaviour of the 10% PC replacement mixes, the 5% excess F and C in the 20% PC replacement mixes (25F/80PC and 25C/80PC) resulted in reduced mass than the convention 20% PC replacement mixes (20F/80PC and 20C/80PC). Therefore, it can be implied that resistance to mass deterioration of PBCW blended cement concrete improves with the increased replacement of PC with PBCW. It can be explained that increased PBCW content in concrete from increase PC replacement results to increase absorption of water by the PBCW been a clay product causing it to become sticky thereby avoiding the washing away of cement hydration product resulting from the acid attack.

DOI:10.4186/ej.2018.22.2.83



	PCC	10F/90PC	15F/90PC	10C/90PC	15C/90PC	20F/80PC	25F/80PC	20C/80PC	25C/80PC
30 days	2.55	3.85	3.58	1.92	1.33	-6.55	1.61	0.13	1.89
60 days	4.67	1.15	0.75	1.54	0.26	-4.71	-1.75	-2.29	-1.7
90 days	5.04	0.89	0.68	1.27	0.13	-4.15	-1.52	-1.65	-1.35

Mix

Fig. 6. Percentage mass loss of cube samples in sulphuric acid.

Plate 1: Acidic attack on PCC after 90 days period.

Plate 2: Acidic attack on 10F/90PC after 90 days period.

Plate 3: Acidic attack on 15F/90PC after 90 days period.

Plate 4: Acidic attack on 10C/90PC after 90 days period.

Plate 5: Acidic attack on 15C/90PC after 90 days period.

Plate 6: Acidic attack on 20F/80PC after 90 days period.

Plate 7: Acidic attack on 25F/80PC after 90 days period.

Plate 8: Acidic attack on 20C/80PC after 90 days period.

Plate 9: Acidic attack on 25C/80PC after 90 days period.

5. Conclusions

The effect of pulverized burnt clay waste (PBCW) fineness on the compressive strength and durability properties of blended cement concrete has been studied. The main conclusions are listed below.

- The compressive strength of PBCW blended cement concrete can be improved with an increase in PBCW fineness. The increase result from the reduced average pore size of the cement paste and the improved interfacial zone caused by the fine PBCW filling the small voids in the pore structure.
- Mix composition of 15F/90PC gave the highest compressive strength of 25 MPa at 28 days water curing compared to other PBCW blended concrete with lesser strength. Hence, it can effectively be used for strength Class C20/25 according to Eurocode 2 suitable for reinforcing concrete works.
- Improved fineness further resulted to the improvement of the material transport properties of the blended cement concrete through the discontinuation of the interconnected pore, resulting into reduced permeability leading to a reduction in chloride penetration and improved resistance to the sulphuric acid attack on strength deterioration and mass loss.
- Furthermore, the compressive strength, resistance to chloride penetration and sulphuric acid attack are improved much more by increasing the PBCW content beyond the conventional replacement level of Portland cement by up to 5% for a total binder of 105%. The improved properties using excess binder content is achieved better with the increased fineness of PBCW and especially at 10% Portland cement replacement.

Incorporation of PBCW in concrete has been shown to improve durability performance of concrete. However, for further studies, it is recommended that the porosity and the ITZ of PBCW blended cement concrete be investigated to give more information on the concrete structure and to validate if the improve durability relates to improves ITZ.

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