Effect of Locust Bean Pod Ash and Eggshell Ash on the Mortar Compressive and Flexural Strengths of Cement Blends

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Abstract. An increase in the generation of biogenic wastes such as locust bean pods and eggshells coupled with the need to drive sustainability in the cement industry has led the use of these wastes as cement replacement materials. The paper aims to investigate the effect of locust bean pod ash (LBPA) and eggshell ash (ESA) on the mortar compressive and flexural strength of ternary cement blends. The LBPA was obtained by calcining locust bean pod (LBP) at various temperatures of 800-900 °C and time of 60−120 minutes at an interval of 50 °C and 30 minutes respectively to determine the optimal conditions. The chemical composition of Ordinary Portland cement (OPC), LBPA and ESA were obtained via X-ray Fluorescence (XRF) Spectrometer and LBPA chemical composition did not satisfy one of the requirements specified by ASTM C618-01 (2001) with SiO_2+ Al_2O_3+Fe_2O_3 of 30.42 wt. % which is less than 50 wt. %, but satisfies SO_3 content requirement of 0.7 wt. % and Loss on Ignition (LOI) of 7.12 wt. % and contains 19.42 wt. % CaO which is within the range of 10-30 wt. % CaO is class C pozzolan. The compressive strength of blended cement mortars at the early age of 2 and 7 days produced better strengths for cement blends with higher ESA content than LBPA especially at LBPA/LBPA-ESA ratio of 0, 0.4 and 0.6 for 2.5 wt. % cement replacement respectively. The early strength gain could be attributed to the provision of more nucleation sites by ESA inclusion which results in the acceleration of cement hydration rate. On the other hand, the enhanced strengths at 28 days of cement blended with various replacement from 2.5−10 wt. % could be attributed to the pozzolanic reaction between the available lime and reactive silica from LBPA despite clinker diminution which was close to control. Another reason for enhanced strength' could be attributed to the increased potassium content by an increase in LBPA content resulting in a gradual strength gain (retarder) muscovite formation $K_2Al_2Si_6Al_4O_{20}(OH)_4$. All cement blends experienced an increase in the mortar compressive and flexural strengths as the curing day progressed with some blends producing enhanced strength compared to control especially with 1.5 ESA1LBPA produced the best strength at 50.15 (6.82) N/mm^2 against 48.80 (6.80) N/mm^2. This enhanced strength could be related to the pozzolanic activity and the high potassium content from LBPA despite clinker diminution, especially at 28 days.

Keywords: Locust Bean Pod Ash; Eggshell Ash; Compressive Strength; Flexural Strength Pozzolan; Flexural Strength; Cement blends.

INTRODUCTION

The demand for cement arising from inadequate housing coupled with the need to solve the problem of release of CO_2 leading to the greenhouse effect and an enormous amount of energy is required for cement production. Cement is a widely employed construction material owing to its sta-bility and flexibility in designs of building structures with advantages ranging from built-in fire resistance, high compressive strength to low maintenance [31]. One alternative solution to these challenges is the partial replacement of cement by appropriate materials such as pozzolans. These pozzolanic materials are siliceous or aluminous materials that themselves have lit-

tle or no cementitious properties but when in finely divided form and the presence of moisture reacts with $CaOH_2$ which is liberated during cement hydration at ordinary temperature to form more cementitious materials according to [7]. Pozzolan possesses the characteristics of reacting with free lime released during cement hydration to form stable insoluble calcium silicates to reduce sulfate, salt and chloride attacks [22]. Researches in cement and concrete technology have concentrated on the use of waste materials as a potential replacement as alternatives for cement in the concrete industry and the need to introduce new materials or recycled materials as cement replacement materials are gaining popularity and as a result of increasingly stringent environmental legislation [2]. Pozzolanic activity of a material can be assessed by the ability of the material to react with $Ca(OH)_2(CH)$ by monitoring the consumption of CH or measuring the strength development. The pozzolan influence is dependent on the quality and quantity of active phases in the pozzolan [10].

Agricultural wastes generated from poultry farms, bakeries, confectioneries, and restaurants which can cause environmental pollution, if not properly disposed of. The increasing demand for cement can address the problem of dumping waste and drive sustainability via the proper utilization or recycling of these biogenic wastes such as eggshell ash. Eggshell ash is byproducts of agricultural wastes obtained from the calcination of eggshell powder at 500 °C to produce calcium oxide which has shown according to [20] that it is a good accelerator, thereby decreasing the setting time of cement [14]. Eggshell is composed of mostly 93.7 % of calcium carbonates and other constituents like phosphates and magnesium which is similar to limestone, thus can be employed as a partial cement replacement material [2, 23]. Authors [20] investigated the effect of ESA from 0–2.5 wt. % at an interval of 0.5 wt. % on setting time of cement blend and observed that setting was accelerated as the ESA content was increased. They also observed that percentage reduction from 1.4–32 wt. % and 2.83–34 wt. % for the initial and final setting times respectively as cement is replaced with the ESA content from 0-2.5 wt. %. Authors [19] investigated the effect of ESA for cement replacement from 5–30 wt. % at an interval of 5 wt. % on the concrete compressive strength and found that 10 wt. % ESA cement blend produced an enhanced strength of 32.36 % and 23.43 % for 7 and 28 days compared with control. Authors [9] also investigated the replacement of cement with ESA from 1–5 wt. % at an interval of 1 wt. % and observed a similar trend of accelerated setting time as the ESA content was increased. It was also concluded that up to 3 wt. % cement replacement with ESA produced a better strength compared with control. Authors [14] investigated the feasibility and viability of employing ESA and its effects on the water consistency and setting time of cement blend and It was seen that both setting time of the cement blended with ESA was shortened as the ESA content was increased from 0–2 wt. % at an interval of 0.5 wt. %.

Locust bean pod husks are byproducts of agricultural wastes obtained from locust bean trees which are deciduous trees mostly grown and harvested in the Sub-Sahara Africa region as well as the Northern part of Nigeria [1]. The improper disposal of various agricultural waste such as rice husk, groundnut husk, corn cob, and locust beans is an environmental concern and thus, the necessity to convert these waste to useful materials since many calcined agricultural wastes are rich in amorphous silica such as rice husk ash, coal bottom ash, fly ash, groundnut shell ash, etc. [13, 15, 18, 24, 26]. These biomasses could be employed as partial cement replacement materials due to their potentials of enhancing the strength of cement blends despite clinker diminution as a result of the reaction of amorphous silica with available lime from ordinary cement hydration [18, 24]. Authors [3] investigated the replacement of cement with up to 50 wt. % LBWA at an interval of 5 wt. % on the concrete strength and observed that an increase in the strength as the curing day progressed from 2 to 28 days for all cement blends with a higher strength value obtained at 28 days. The general trend was that the concrete compressive strength diminished steadily as the % LBWA was gradually increased with cement replacement not up to 10 wt. % providing the targeted concrete compressive strength of 20 N/mm^2. Authors [5] studied the use of LBWA as partial cement replacement in concrete structures and observed that as the cement replacement with LBWA led to a decrease in the concrete strength for grade 20, 25 and 30 with an increase in strengths as the curing days progressed. It also observed that beyond 10 wt. % cement replacement with LBWA, the concrete compressive strength at 28 days for grades 20, 25 and 30 were 22.33, 24.38 and 24.22 N/mm^2 respectively. Authors [4] investigated the effect of replacing LBPA on the setting times and ob-

served that as the LBPA content increased up to 30%, the initial and final setting time experienced retardation by 66.8 % and 39.7 % respectively while LBPA cement blends beyond 15 wt. % resulted in a decrease in its concrete compressive strength in a decrease in its concrete compressive strength while the concrete mix workability diminished as the LBPA content was increased. The enhanced compressive strength of 15 wt. % LBPA cement blend agreed with results from SEM – EDS and XRD which indicated Calcium Silicate Hydrate (C-S-H) gel compared to other samples. They also suggested that the nature of the LBPA in terms of the crystalline or amorphous influenced the setting time which was dependent on the process of obtaining the ash. Authors [17] observed that 7 days' strength of control was better than LBPA cement mortar since the hydration rate of OPC was more rapid compared with LBPA cement blends while the cement replacement with up to 12 wt. % LBPA produces similar compressive strength in comparison with control. Authors [21] investigated the effect of replacing cement with LBPA between 0–25 wt. % at a 5 wt. % interval and observed a decrease in the compressive strength by 46 % as the LBPA was increased up to 25 wt. % while 5 wt. % LBPA cement blend produced similar strength to control. Authors [32] indicated that as the concentration of KCl was increased from 0–14 g/l, the concrete compressive strength of the OPC concrete increased for all 28 and 90-days results. They suggested that the probable chemical reaction for the hydration of cement with K concentration is the reason for the retardation of the setting time attributed to the formation of muscovite. $K_2Al_2Si_6Al_4O_{20}(OH)_4$ and the large size of potassium ions involved in the crystallization of muscovite leading to an increase in the void. Thus, the presence of K^+ ions results in retardation of the initial and final setting time.

MATERIALS

Superset cement CEM II A-L conforms to the NIS 444 standards obtained from Ashaka cement ltd, Gombe state. Eggshells were collected from chick hatcheries, bakeries, fast food joints and restaurants. The eggshell ash (ESA) was prepared by burning fowls' eggshells at a temperature of 500 °C for 1 hour to obtain complete ash while Locust bean pods (LBP) were collected from Badabdi community, Gombe state, Nigeria. The fine aggregate used was CEN-NORMSAND (DIN EN 196-1) which conforms to ISO 679 with a net

weight of 1350±5g as standard sand. The distilled water was employed for mortar preparation and a well quantifiable amount for paste preparation. Water is needed for the hydration reaction of cement and also to make it workable during mixing. Table 1 indicates the chemical composition of OPC, LBPA, and ESA while Table 2 presents the chemical composition of the various locust bean pod ash calcined at 800, 850 and 900 °C at 1 and 2 hours respectively.

Table 1 − Chemical composition of Portland Cement, Locust bean pod ash and Eggshell ash

Oxides	OPC, wt. %	LBPA, wt. %	ESA, wt. %
SiO_2	23.87	9.48	0.19
Al_2O_3	7.87	2.00	0.54
Fe_2O_3	3.94	18.94	0.34
CaO	57.34	19.42	49.58
MgO	1.76	5.95	0.82
SO_3	1.05	0.70	0.51
K_2O	0.00	27.54	0.40
Na_2O	0.36	0.44	-
P_2O_5	-	7.71	-
Mn_2O_3	-	0.29	-
TiO_2	-	0.15	-
Cl	-	0.02	-
Cr_2O_3	-	0.04	-
SrO	-	0.14	-
LOI	3.81	7.19	47.62
$CaCO_3$			88.49
Sum of Conc.	100.00	100.00	100.00

Table 2 − Chemical composition of different calcination temperature and time of LBPA

Compounds	800 °C		850 °C		900 °C	
	1 hr.	2 hrs.	1 hr.	2 hrs.	1 hr.	2hrs.
SiO_2	6.66	6.48	9.48	9.43	9.44	9.69
Al_2O_3	3.28	3.34	2.00	2.98	1.90	1.73
Fe_2O_3	19.71	19.48	18.94	17.79	17.74	17.09
CaO	18.37	18.33	19.42	18.58	18.40	18.19
MgO	6.50	6.50	5.95	5.77	7.28	7.29
SO_3	1.89	1.86	0.70	1.47	0.67	0.66
K_2O	26.42	26.39	27.54	27.75	26.44	27.39
Na_2O	1.47	1.47	0.44	0.50	0.43	0.33
P_2O_5	7.95	7.83	7.71	7.59	8.16	7.58
Mn_2O_3	2.82	2.83	0.29	0.28	0.31	0.29
TiO_2	0.06	0.07	0.15	0.15	0.21	0.15
Cl	0.02	0.03	0.02	0.03	0.04	0.03
Cr_2O_3	0.06	0.08	0.04	0.04	0.05	0.04
SrO	0.19	0.15	0.14	0.15	0.15	0.15
LOI	4.61	5.16	7.19	7.50	8.79	9.40
Sum Total	100	100	100	100	100	100

PROCEDURE

The locust bean pods were dried under the sun for three days, crushed to about 0.5 mm size using the jaw crusher and then burnt locally using charcoal-burner though the pod was not allowed to make contact with the charcoal. Ten grams (10 g) of the initially burnt locust beans sample were weighed and then placed in an electric furnace. The samples were then calcined at different temperatures (800 °C, 850 °C & 900 °C) for 1 hour & 2 hours respectively to obtain the optimum temperature and time. Eggshells obtained from bakeries were sorted, sun-dried and crushed with a mortar and pestle. The ground eggshell powder was then calcined at a temperature of 500 °C at 1 hr. The resultant ashes from the calcination of the locust bean and eggshell powder were analyzed via a fused bead machine for the oxide analysis. One-gram (1 g) of the samples to be analyzed were weighed into a clean dry platinum crucible and 8 grams of X-ray flux (Granular) type Lithium tetraborate 66 % and lithium metaborate 34 % was weighed and mixed thoroughly with the sample. 1 ml of 25 % LiBr solution using a 1ml pipette was added to avoid the sample from sticking to the platinum crucible. The prepared samples were then placed in VFD 4000 Fused Bead Machine and the machine was set ON for the process to begin. The beads were well labeled for proper identification and then ran through the XRF spectrometer on a reference curve program and the results were obtained. The ash content was purely obtained and the percentage loss was calculated for each of the heated samples and the optimum condition was determined at 850 °C for 1 hour.

Mortar compressive strengths of various cement blends were determined by compressive strength tests on mortar cubes compacted using a standard vibration machine. Standard sand was used for the preparation of cement mortar with the specimens set in 70.6 mm cubes (EN 196-1). The compressive strength tests of mortar samples were determined according to ASTM specification C39 after 2, 7 and 28 days of standard curing. The test specimens are stored in moist air climatic chamber at 20 °C for 24 hours, after which it was removed, marked and submerged into clear fresh water at 20±2 °C until curing days at 2, 7 and 28 days. The water for curing was monitored daily to maintain the temperature as specified. The flexural strength tests were achieved by performing a surface point test on the prism by EN 1052-2 by applying load horizontally on the prism by a hydraulic jack. The pictures of dried eggshell, standard sand, eggshell ash, locust bean pod ash are shown in Figures 1–4 respectively.

Experimental Design Mix. The experimental matrix for LBPA-ESA cement blends with cement replacement between 0-10 wt. % is presented in Table 3. Resource [6] standard mix ratio of mortar cubes which can be employed for internal walls and surfaces of great importance was adopted for this study. A water/cement ratio of 0.4 was employed in molding mortar cubes comprising of ESA of 2.5 wt. %, 5 wt. %, 7.5 wt. % and 10 wt. % which was gradually replaced with LBPA for different mixes.

Figure 1 – Dried Eggshell

Figure 2 – Standard Sand EN 196-1

Figure 3 – Eggshell Ash

Figure 4 – Locust Beans Pod Ash

RESULTS AND DISCUSSION

The chemical composition obtained from the XRF analysis of OPC, LBPA, and ESA were presented in Table 1. The percentage of reactive silicates content of CEM II A-L 42.5 N contains 23.87 wt. % which is higher than 9.48 wt. % for LBPA. The results of the chemical composition of LBPA indicates that it does not satisfy most requirements specified by [8] with 30.41 wt.% of $SiO_2+Al_2O_3+Fe_2O_3$ which is less than 50 wt.% but satisfies the other requirements such as SO_3 content of 0.7 wt. % which is less than the maximum of 5 wt. % and LOI of 7.12 wt. %, it contains 19.42 wt. % CaO which is within the range of 10–30 wt. % CaO which fall into class C pozzolan. A similar trend was observed for [16] but obtained a lower $SiO_2+Al_2O_3+Fe_2O_3$ content of 25 wt. %. The XRF analysis of the calcined eggshell (ESA) reveals a high amount of CaO of 49.58 wt. % ($CaCO_3$ 88.49 wt. %) along with minute quantities of SiO_2, Al_2O_3, Fe_2O_3, MgO, SO_3, K_2O and Na_2O below 1 wt. % while ESA LOI was 47.62 wt. % which was high indicating the presence of non- decomposed limestone.

Author [33] revealed that eggshell was mainly composed of 93.70 wt. % calcium carbonate, 4.20 wt. % organic matter, 1.30 wt. % magnesium carbonate, and 0.8 wt. % of calcium phosphate. According to authors [30], the decomposition of $CaCO_3$ to CaO (lime) was evident at about 820 °C in which $CaCO_3$ is the main constituent and at 500 °C, the weight loss of the calcined ESP could be due to dehydration of water and loss of organic matter to produce ESA.

Table 3 – Experimental Matrix for the various cement blends

No	Blends	LBPA / LBPA ESA	ESA, wt. %	LBPA, wt. %	OPC, wt. %	ESA, g	LBPA, g	OPC, g
1	0ESA0LBPA	0	0	0	100	0	0	500
2	2.5ESA	0	2.5	0	97.5	12.5	0	487.5
3	2ESA0.5LBPA	0.2	2	0.5	97.5	10	2.5	487.5
4	1.5ESA1LBPA	0.4	1.5	1	97.5	7.5	5	487.5
5	1.25ESA1.25LBPA	0.5	1.25	1.25	97.5	6.25	6.25	487.5
6	1ESA1.5LBPA	0.6	1	1.5	97.5	5	7.5	487.5
7	0.5ESP2LBPA	0.8	0.5	2	97.5	2.5	10	487.5
8	2.5LBPA	1	0	2.5	97.5	0	12.5	487.5
9	5ESA	0	5	0	95	25	0	475
10	4ESA1LBPA	0.2	4	1	95	20	5	475
11	3ESA2LBPA	0.4	3	2	95	15	10	475
12	2.5ESA2.5LBPA	0.5	2.5	2.5	95	12.5	12.5	475
13	2ESA3LBPA	0.6	2	3	95	10	15	475
14	1ESP4LBPA	0.8	1	4	95	5	20	475
15	5LBPA	1	0	5	95	0	25	475
16	7.5ESP	0	7.5	0	92.5	37.5	0	462.5
17	6ESA1.5LBPA	0.2	6	1.5	92.5	30	7.5	462.5

No	Blends	LBPA / LBPA ESA	ESA, wt. %	LBPA, wt. %	OPC, wt. %	ESA, g	LBPA, g	OPC, g
18	4.5ESA3LBPA	0.4	4.5	3	92.5	22.5	15	462.5
19	3.75ESA3.75LBPA	0.5	3.75	3.75	92.5	18.75	18.75	462.5
20	3ESA4.5LBPA	0.6	3	4.5	92.5	15	22.5	462.5
21	1.5ESA6LBPA	0.8	1.5	6	92.5	7.5	30	462.5
22	7.5LBPA	1	0	7.5	92.5	0	37.5	462.5
23	10ESA	0	10	0	90	50	0	450
24	8ESA2LBPA	0.2	8	2	90	40	10	450
25	6ESA4LBPA	0.4	6	4	90	30	20	450
26	5ESA5LBPA	0.5	5	5	90	25	25	450
27	4ESA6LBPA	0.6	4	6	90	20	30	450
28	2ESA8LBPA	0.8	2	8	90	10	40	450
29	10LBPA	1	0	10	90	0	50	450

Table 4 presents some determining physical properties of the cement CEM II A-L 42.5N while the mortar compressive and flexural strengths of control specimen and 28 cement blends at various curing ages were determined and presented in Table 5.

Table 4 − Physical Properties of Control Sample (CEM II A-L 42.5N)

Property			
Curing age, days	2	7	28
Compressive Strength (N/mm²)	23.84	38.99	48.18
Flexural Strength (N/mm²)	4.46	6.13	6.80
Setting Time (mins) Initial setting	117	Final setting	186
Water Consistency (%)		29	
Expansion (mm)		0	

Table 5 − Mortar Compressive and Flexural strengths of various cement blends and curing ages

No	Blends	Compressive Strength (Flexural Strength) N/mm²		
		2-days	7-days	28-days
1	OPC	23.84 (4.46)	38.99 (6.13)	48.18 (6.80)
2	2.5ESA	27.93 (4.61)	34.46 (5.80)	53.19 (7.33)
3	2ESA0.5LBPA	21.03 (3.91)	34.60 (5.35)	46.44 (6.42)
4	1.5ESA1 LBPA	26.74 (4.43)	32.77 (4.85)	50.15 (6.82)
5	1.25ESA1.25 LBPA	21.91 (4.00)	29.05 (4.25)	47.21 (6.44)
6	1ESA1.5 LBPA	24.21 (4.38)	30.27 (4.51)	47.32 (6.71)
7	0.5ESP2LBPA	22.37 (4.30)	31.4 (4.80)	45.19 (6.37)
8	2.5LBPA	23.18 (4.31)	31.85 (4.37)	46.00 (6.43)
9	5ESA	27.93 (5.10)	37.35 (6.10)	44.95 (6.30)

No	Blends	Compressive Strength (Flexural Strength) N/mm²		
		2-days	7-days	28-days
10	4ESA1LBPA	21.46 (4.26)	29.69 (4.79)	43.00 (6.20)
11	3ESA2LBPA	22.18 (3.70)	35.46 (5.92)	46.58 (6.55)
12	2.5ESA2.5LBPA	17.16 (3.33)	30.80 (4.54)	39.83 (6.37)
13	2ESA3LBPA	21.01 (3.37)	34.46 (5.80)	46.57 (6.50)
14	1ESP4LBPA	23.08 (4.14)	30.60 (4.19)	47.20 (6.37)
15	5LBPA	18.1 (3.74)	35.4 (5.21)	40.09 (6.21)
16	7.5ESP	17.77 (3.40)	32.77 (4.85)	45.13 (6.41)
17	6ESA1.5LBPA	21.93 (3.75)	34.25 (5.11)	46.62 (6.51)
18	4.5ESA3LBPA	19.11 (3.62)	33.19 (5.42)	48.10 (6.71)
19	3.75ESA3.75LBPA	18.65 (3.57)	29.67 (4.79)	35.76 (6.19)
20	3ESA4.5LBPA	16.89 (3.01)	32.79 (4.11)	47.20 (6.65)
21	1.5ESA6LBPA	21.65 (4.40)	32.51 (5.75)	38.75 (6.42)
22	7.5LBPA	23.20 (4.61)	34.30 (5.49)	41.92 (6.03)
23	10ESA	23.71 (4.42)	36.52 (5.16)	43.18 (6.99)
24	8ESA2LBPA	23.19 (4.38)	33.66 (5.71)	48.00 (6.75)
25	6ESA4LBPA	23.43 (4.09)	34.29 (5.62)	42.14 (6.24)
26	5ESA5LBPA	26.47 (4.76)	32.72 (4.79)	41.28 (6.07)
27	4ESA6LBPA	23.13 (4.20)	34.97 (5.24)	45.70 (6.58)
28	2ESA8LBPA	22.75 (4.42)	35.26 (5.80)	47.10 (6.77)
29	10LBPA	23.06 (4.59)	34.54 (6.26)	43.18 (6.99)

Compressive strength of cement blended with ESA and LBPA. Figure 5 indicated that for 2.5 wt. % cement replacement at 2 days, cement blends with higher ESA content produced better mortar compressive strengths than those with higher LBPA content especially at LBPA/LBPA-ESA ratios of 0, 0.4 and 0.6 respectively. Similar trends were observed for the ESA cement blend and limestone cement blend employed in [24] work.

This early strength of the cement blended with ESA (the calcium oxide present in ESA which is similar to limestone) could be attributed to the provision of more nucleation sites via the production of calcium hydroxide (CH) at the early stage coupled with additional lime from ESA inclusion [11, 29] resulting in acceleration of the hydration rate, thereby resulting in accelerated early strength [27, 28].
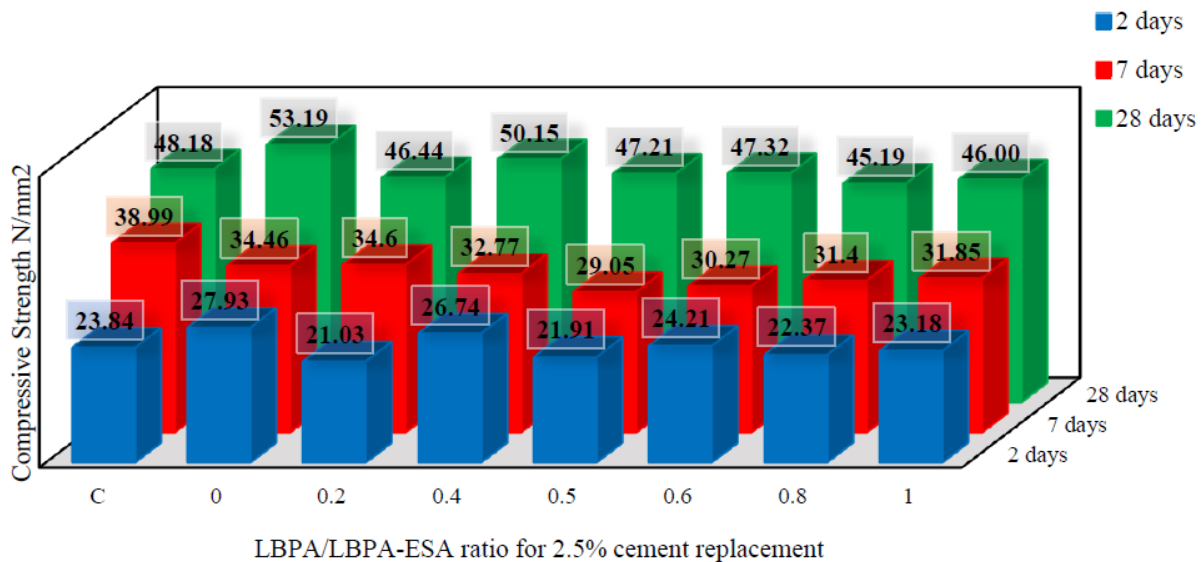
Figure 5 – Variation of SCM content and curing age on the mortar compressive strength at 2.5 % cement replacement

Similarly, works by [13, 26, 12] indicated that the inclusion of ESA (similar to limestone powder) could lead to the formation of monocarbonate, thus stabilizing ettringite at the expenses of monosulphate, thereby increasing the volume of the hydrates and in turn enhance its compressive strength of the cement blended with ESA. All cement blends at 2 days produced compressive strengths above 91 % of the control strength as illustrated in Figure 5. The 7 days compressive strength for cement blends also produced better strengths for cement blends containing more ESA content than LBPA content with neither better than control.

It was also observed that the 28-day mortar compressive strength produced two cement blends with enhanced strength of 53.19 N/mm² and 50.15 N/mm² as against to control of 48.18 N/mm² at LBPA/LBPA-ESA ratio of 0 and 0.4 respectively. This enhanced strength could be

attributed to the pozzolanic reaction from available lime and silica from LBPA despite diminution of clinker content resulting in the enhanced strength which was close to control. It could also be suggested that an increase in potassium content due to an increase in LBPA results in a gradual strength gain (retarder) due to the formation of muscovite $K_2Al_2Si_6Al_4O_{20}(OH)_4$ [32] despite clinker diminution. The mortar compressive strength of all the blends experienced an increase as the curing day progressed as illustrated in Figures 6–8 respectively.

Figures 6–8 showed that all mortar compressive strengths at 2, 7 and 28 days for cement blends beyond 5 wt. % replacement were either slightly or significantly lower than the control except for LBPA/LBPA-ESA ratio of 0.0 for 5 wt. % cement replacement which produced a better 2 days compressive strength of 27.93 N/mm² against control compressive strength of 23.84 N/mm².
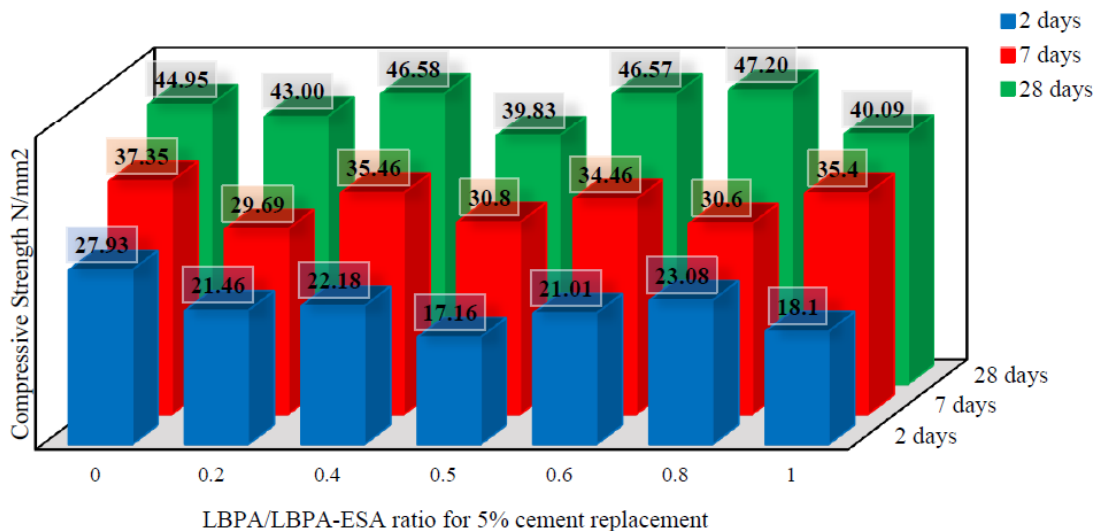
Figure 6 − Variation of SCM content and curing age on the mortar compressive strength at 5 % cement replacement
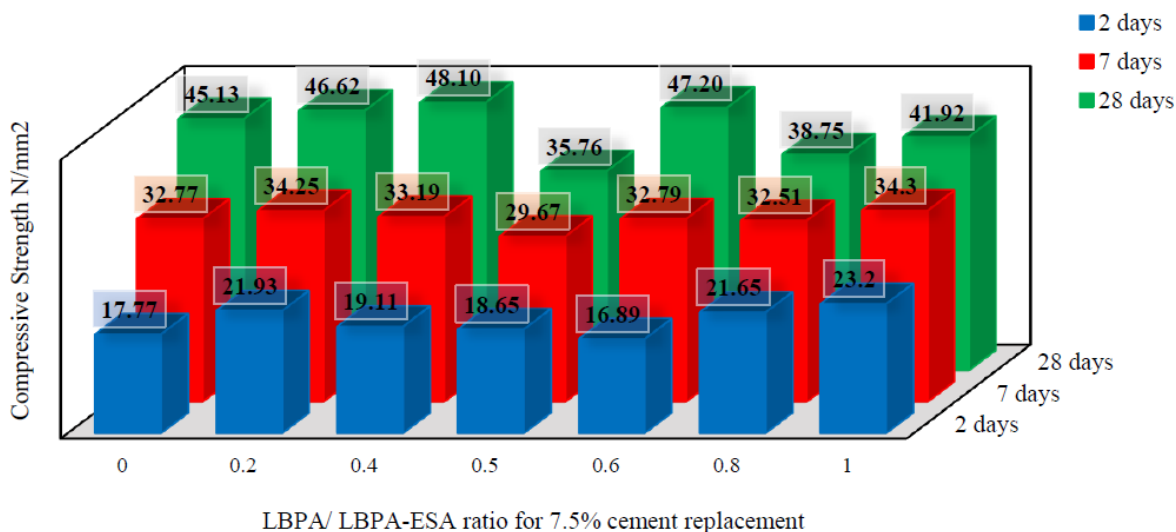

Figure 7 − Variation of SCM content and curing age on the mortar compressive strength at 7.5 % cement replacement
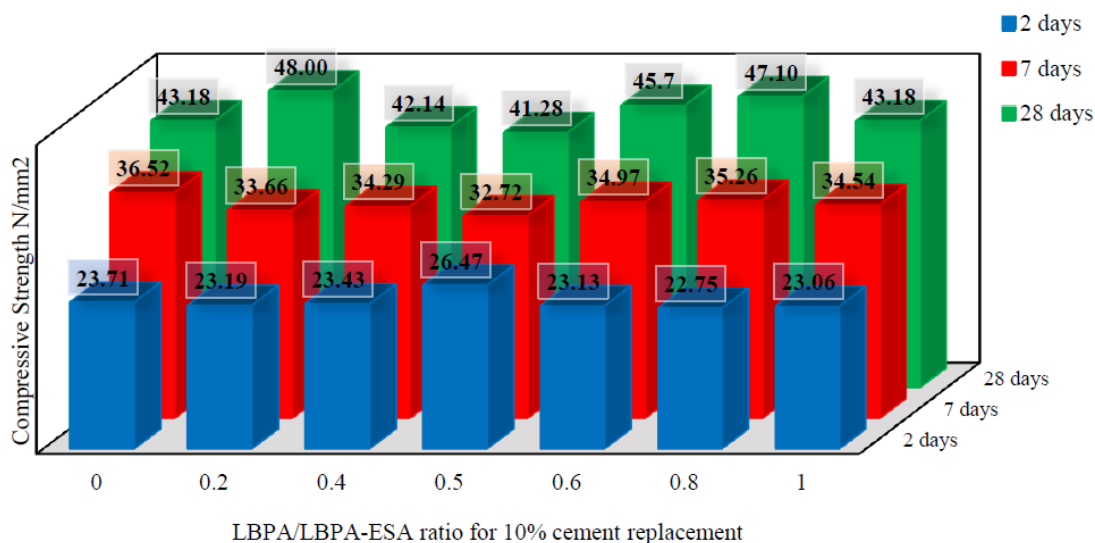

Figure 8 − Variation of SCM content and curing age on the mortar compressive strength at 10 % cement replacement

The reason for the enhanced strength despite cement replacement of 5 wt.% could be attributed to the pozzolanic reaction between the available lime from the hydration of calcium silicate and the silica present in the LBPA, resulting in the formation of more CSH, leading to a denser and an enhanced strength which is in agreement with [24, 26] coupled with the formation of muscovite which also enhances the mortar compressive strength [32] as illustrated in equation (1).

$$K^+ + 3Al_2O_3 + 7SiO_2 + 2H_2O \rightarrow K_2Al_2Si_6Al_4O_{20}(OH)_4 + SiO_2^- \quad (1)$$
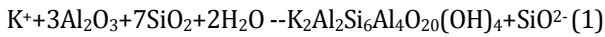
Similar trends of improved strength despite the reduction in the clinker content were observed for 7.5 wt. % and 10 wt. % cement replacement with LBPA and ESA as illustrated in Figures 7 and 8 respectively. The inclusion of CH crystals from ESA on the hydration of calcium silicates tends to enhance the early rate of cement hydration by the provision of more nucleation sites, thereby resulting in accelerated early strength which agrees with [11, 29, 27, 25]. Figure 8 indicated that Cement blends produced enhanced strengths at early ages between 2 and 7 days for LBPA/ LBPA-ESA ratio of 0.4, 0.6 and 1 respectively in comparison with control with hydration rate ranging from 23.6 % to 54.98 % for cement blends compared to 63.55 % for control. Similar mortar compressive strength for blends with

10 wt. % cement replacement compared with the control despite clinker diminution.

Flexural strength of cement blended with ESA and LBPA. The variation of LBPA, ESA content and curing age on the mortar flexural strength of cement blends at various cement replacement of 2.5, 5, 7.5 and 10 wt. % are illustrated in Figures 9–12 respectively. It could be also be observed from Figure 9 for 2.5 wt. % cement replacement, that most of the blends at various LBPA/LBPA-ESA ratios produced slightly lower 28 days strengths compared with control, whereas cement blends with LBPA/LBPA-ESA ratio of 0 and 0.4 produced better strengths of 7.33 N/mm² and 6.82 N/mm² against the control of 6.8 N/mm² despite cement replacement.

Figure 10 indicated most cement blends produced lower 2 days flexural strength at 5 wt. % cement replacement expect ESA cement blend with a flexural strength of 5.10 N/mm² against control strength of 4.46 N/mm². All blends produced lower flexural strengths for 28 days ranging from 6.2–6.55 N/mm² as against 6.8 N/mm² for control with a similar trend of lower 7 days flexural strength of cement blends compared to control at 5, 7.5, and 10 wt. % cement replacement respectively. It also observed that most of the cement blends with 7.5 wt. % cement replacement produced slightly close 28 days flexural strengths compared to control despite clinker diminution as illustrated in Figure 11.
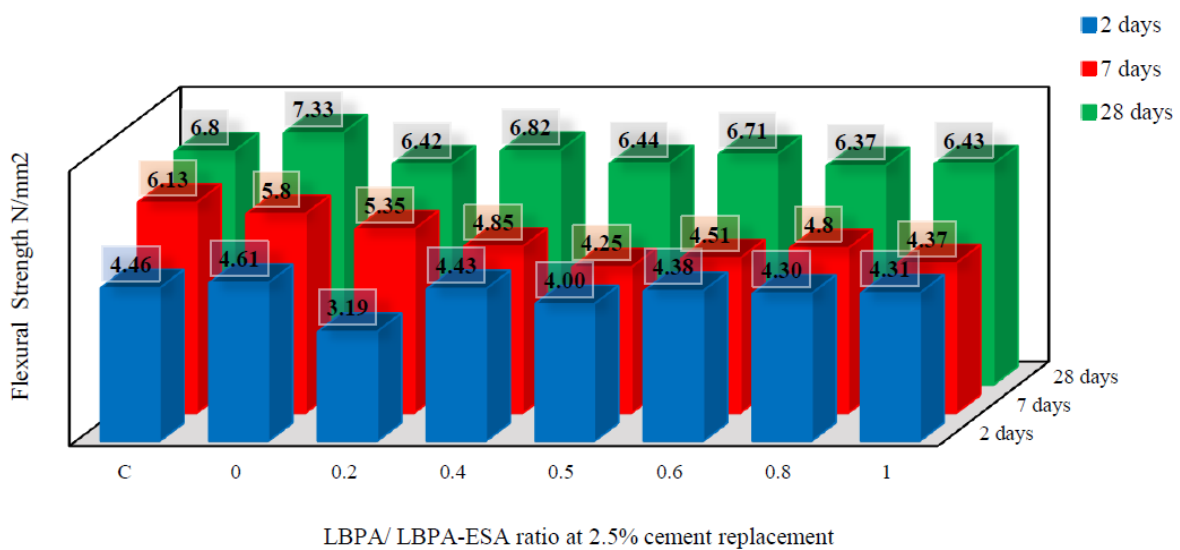

Figure 9 – Variation of SCM content and curing age on the mortar flexural strength at 2.5 % cement replacement
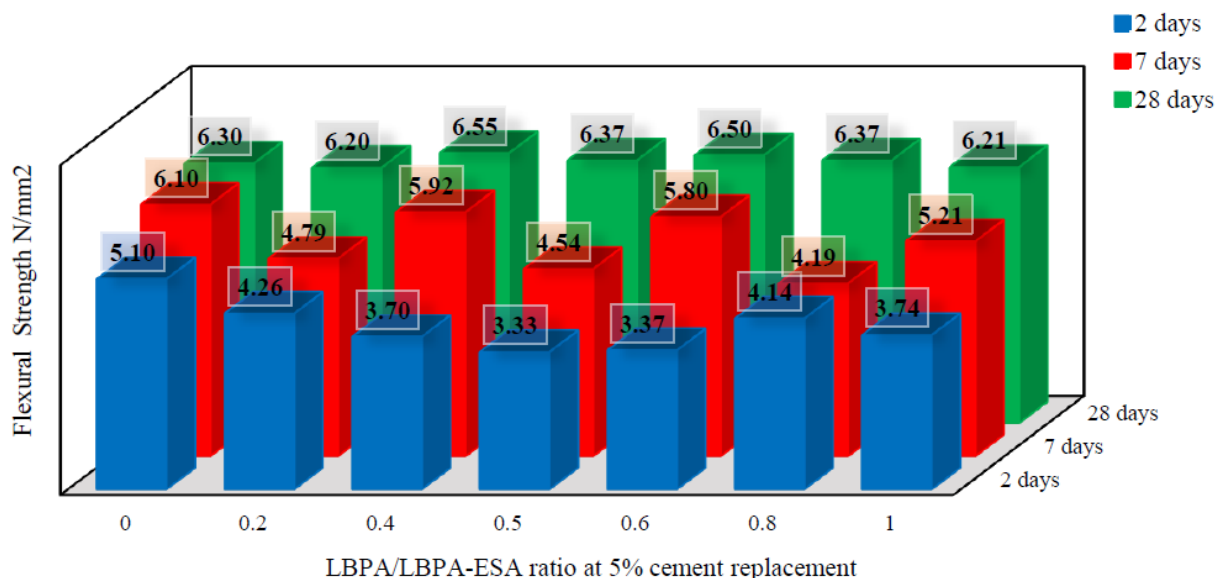
Figure 10 − Variation of SCM content and curing age on the mortar flexural strength at 5 % cement replacement
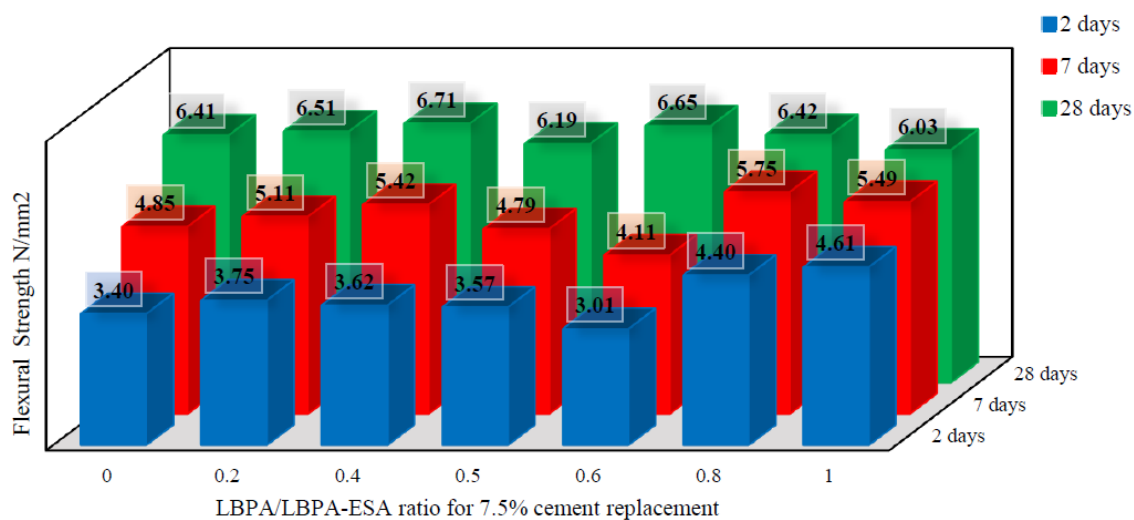

Figure 11 − Variation of SCM content and curing age on the mortar flexural strengths at 7.5 % cement replacement

Figure 12 indicated that despite clinker diminution for 10 wt. % ESA and 10 wt. % LBPA cement blends produced better 28 days flexural strengths of 6.99 N/mm² than control while LBPA/LBPA-ESA ratios of 0.2 and 0.8 produced strength slightly close to the control of 6.75 and 6.77 N/mm² respectively which despite the clinker diminution. Similarly, it was also seen that the 2 days flexural strength for LBPA/LBPA-ESA ratios of 0.5 and 1 produced improved flexural strengths of 4.76, 4.59 N/mm² as against control of 4.46 N/mm² respectively while at

7 days flexural strength for 10 wt. % LBPA cement blend obtained an enhanced strength of 6.26 N/mm² against 6.13 N/mm². This improved strength could be attributed to the pozzolanic activity of the cement blends.

The compressive strength of blended cement was expressed as a percentage of the rate of control cement at the same curing time and illustrated in Figures 13 and 14 for LBPA cement blend and ESA cement blend respectively.
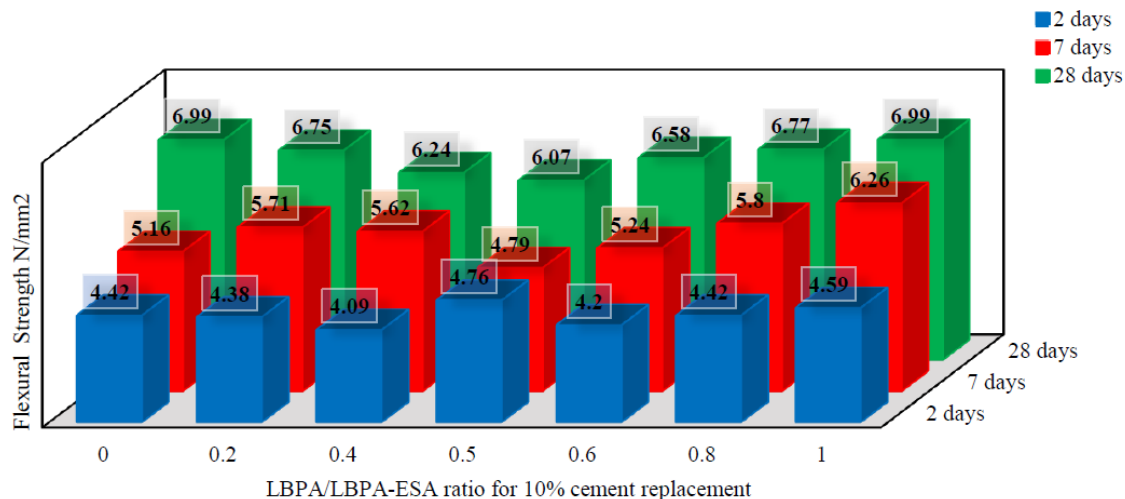
Figure 12 − Variation of SCM content and curing age on the flexural strengths at 10 % cement replacement
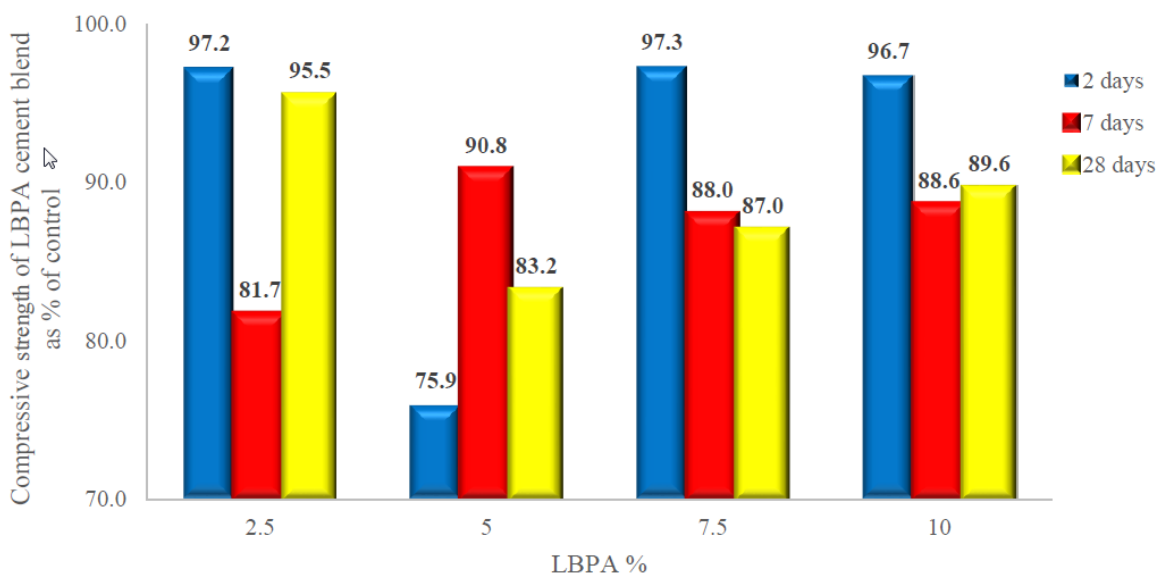

Figure 13 − Compressive Strengths of Blended LBPA as a percentage of control at various ages
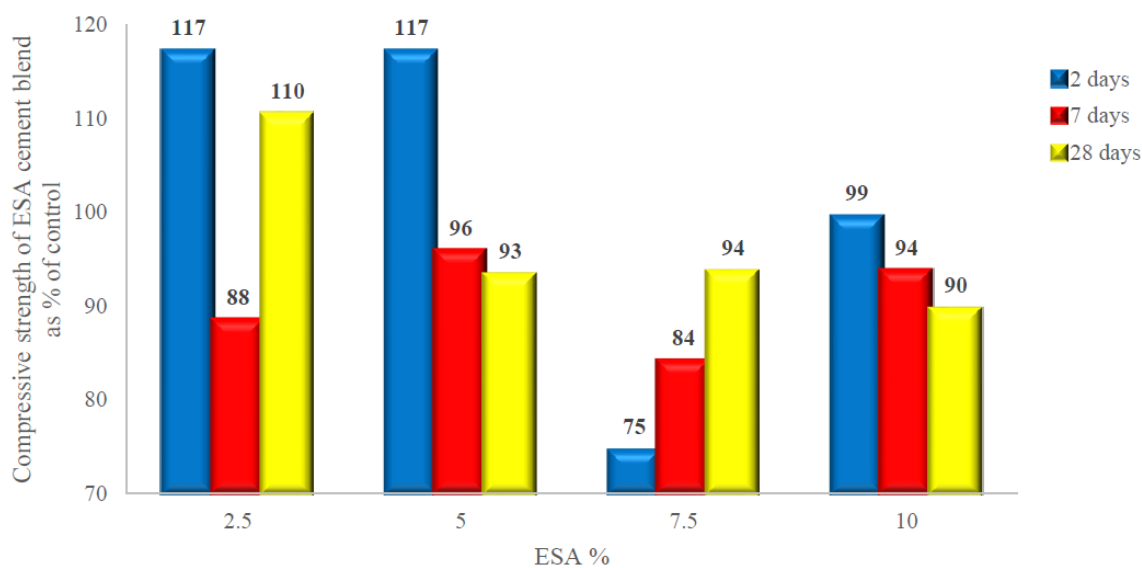

Figure 14 − Compressive Strengths of Blended ESA as a percentage of control at various ages

Cement blended with LBPA for 2.5–10 wt. % at an interval of 2.5 wt. %, all produced mortar strengths lower than those of control at various curing days respectively. It was also seen that cement blended with 10 wt. % LBPA produced up to 90% of the control strength despite clinker diminution is an indication of a pozzolanic reaction between silica present in LBPA and the available CH from cement hydration which is in agreement with [24]. LBPA cement blends of 7.5, 5 and 2.5 wt. % cement replacement produced the best strength of 97.3, 90.8 and 95.5 % of the control strength for 2, 7 and 28 days respectively. Whereas Cement blended with ESA for 2.5–10 wt. % at an interval of 2.5 wt. %, most of the mortar strength produced were lower than those of control except cement blended with 2.5 wt. % and 5 wt. % ESA at 2 days and 2.5 wt. % ESA at 28 days with the best strength of 117, 110, and 117 % respectively. This enhanced strength experienced especially at 2 days could be attributed to the provision of nucleation site, thus accelerating hydration rate which was in agreement with [13] and [26]. ESA cement blends of 2.5 wt. % and 5 wt. % produced strength of 117 % in comparison with control for 2 days, 5 wt. % cement

replacement produced the best strength of 96 % for 7 days whereas 2.5 wt. % cement replacement produced the best strength of 110 % for 28 days.

The flexural strengths for LBPA and ESA as a percentage of control are illustrated in Figures 15 and 16 respectively. It could be observed that as the LBPA content was increased from 2.5–5 wt. %, the flexural strength increased compared with control strength beyond which any further increase led to a lower strength at 2 days. A similar trend was also observed at 7 days with 5 wt. % LBPA producing similar strength with control beyond which produced lower flexural strength whereas, for 28 days flexural strength only 2.5 and 10 wt. % LBPA produced enhanced strength despite cement replacement indicating pozzolanic activity. Similarly, the enhanced strength could be attributed to the presence of potassium, thus increase the flexural strength, especially at 28 days. 5 wt. % LBPA cement blend produced the best 2 and 7 days flexural strength while 2.5 wt. % LBPA cement blend produced the best 28 days as illustrated in Figure 15.
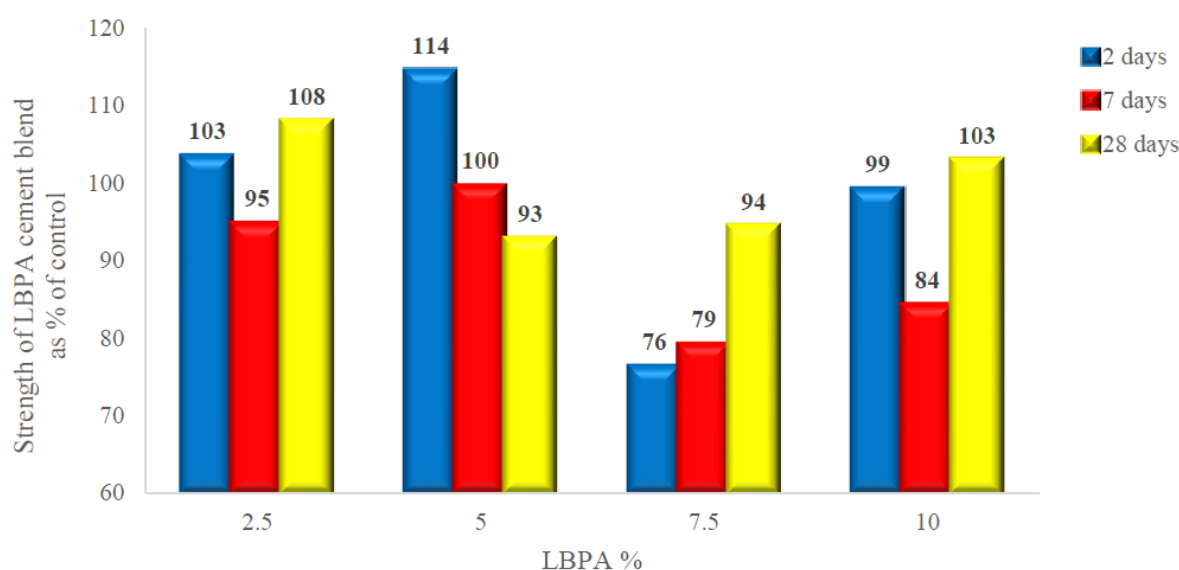

Figure 15 – Flexural Strengths of Blended LBPA as a Percentage of Control at various Ages

The 2 days flexural strength of the ESA cement blend produced enhanced strength at 7.5 wt. % and 10 wt. %. The 7 days strength was seen to increase as the ESA content was increased from 2.5–10 wt. % with only 10 wt. % ESA content producing a better flexural strength than the control. Only 10 wt.% ESA cement blend for 28 days flexural strength produced a better strength than control. This could be attributed to the increased early hydration rate due to the

provision of nucleation sites from the availability of CH present in the matrix [26]. Figure 16 indicates that 7.5 and 10 wt. % ESA cement blends both produced the highest flexural strengths at 2 days as a percentage of control at approximately 103 % respectively. It was also observed that 10 wt. % of cement blended with ESA produced the highest flexural strength as a percentage of the control at 7 and 28 days.
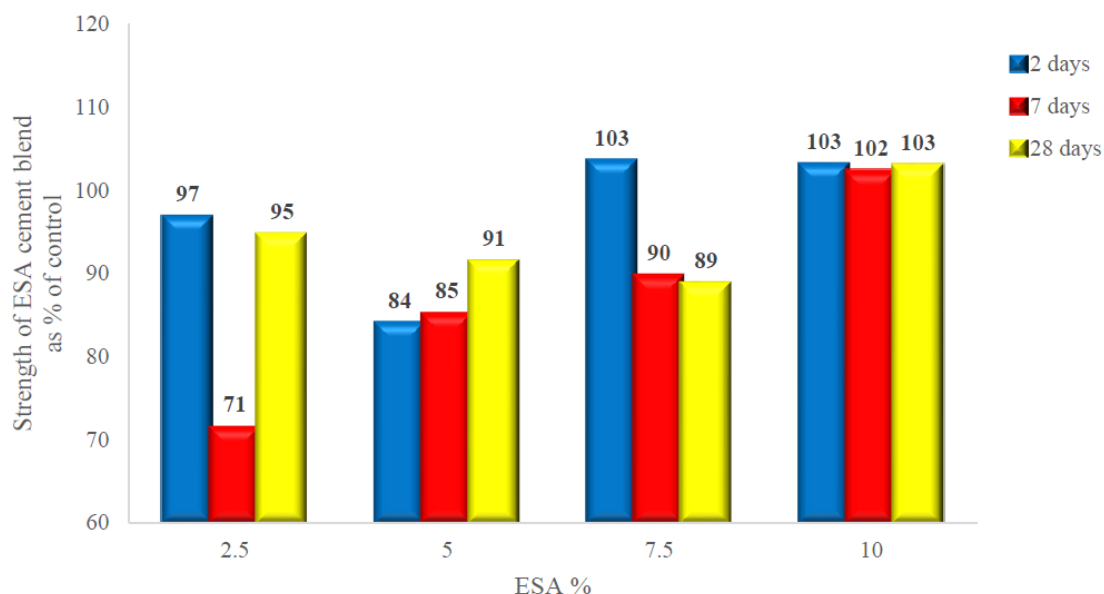
Figure 16 – Flexural Strengths of Blended ESA as a percentage of control at various ages

CONCLUSION

In this study, the potential of blending cement with LBPA and ESA were investigated on the mortar compressive and flexural strength of cement blends and the following conclusions were drawn.

The chemical composition of LBPA did not satisfy one of the requirements specified by ASTM C618 [8] with $SiO_2+Al_2O_3+Fe_2O_3$ of 30.42 wt.% which is less than 50 wt.% but satisfies the other requirements such as SO_3 content of 0.7 wt.% which is less than the maximum of 5 wt.% and LOI of 7.12 wt.% and contains 19.42 wt.% CaO which is within the range of 10-30 wt.% CaO is class C pozzolan. The increase in LBPA content (high potassium content) of cement blends resulted in gradual strength gain (retarder) due to the formation of muscovite $K_2Al_2Si_6Al_4O_{20}(OH)_4$ despite the increased cement replacement with LBPA.

The mortar compressive strength of cement blends at the early age of 2 and 7 days produced better compressive strengths with higher ESA content compared to LBPA especially at LBPA/LBPA-ESA ratio of 0, 0.4 and 0.6 for 2.5 % cement replacement. This better early strength gain could be attributed to the provision of more nucleation sites by the inclusion of ESA, thus accelerating the rate of cement hydration.

On the other hand, the enhanced strengths at 28 days of cement blended with various replacement from 2.5–10 wt. % could be attributed to

the pozzolanic reaction between the available lime and reactive silica from LBPA despite clinker diminution which was close to control. It could also be suggested that an increase in potassium content due to increase in LBPA content could lead to a gradual strength gain (retarder) due to the formation of muscovite $K_2Al_2Si_6Al_4O_{20}(OH)_4.$

An increase in the mortar compressive strength of all cement blends was observed as the curing day progressed. It was also observed that most of the blends experienced an enhanced strength gain compared with control strength gain of 23.57 % between 7 and 28 days while most of the cement blends produced enhanced strength gain ranging from 13.35–62.51 % compared to control. This enhanced strength can be related to the pozzolanic activity which is evident despite clinker diminution coupled with the high potassium content from LBPA could be suggested to be the reason for enhanced strength gain, especially at 28 days according to [32].

A decrease in the mortar compressive strength of LBPA cement blends was experienced as the LBPA content was increased from 2.5 to 10 wt.% compared with control strength which was approximately 90 % of the control strength despite cement replacement of LBPA up to 10 wt.%, while an enhanced strength was observed for cement replacement with ESA for 2.5 and 5 wt.% at 2 days which agrees with the provision of nucleation sites resulting in enhanced early strength. The 28 days compressive strength

was seen to diminish as the cement replacement with ESA was increased from 2.5–10 wt.% at an interval of 2.5 wt.%.

An increase in the flexural strength of LBPA cement blends was observed as the LBPA content was increased up to 5 wt. %, beyond which produced lower 2 and 7 days' flexural strengths compared with control strength respectively. Whereas at 2.5 and 10 wt. % cement replacement with LBPA produced enhanced 28 days' strength compared with control. This enhanced strength could be attributed to pozzolanic activity coupled with the presence of potassium ions despite diminution of clinker content resulting in enhanced strength especially at 28 days. A gradual increase in the 7 days flexural strength experienced a gradual increase as the cement was replaced with ESA content from 2.5-10 wt. % with only 10 wt. % ESA content producing a better flexural strength than the control. This could be attributed to the increased early hydration rate due to the provision of nucleation sites from the availability of CH present in the matrix. The 2 days flexural strength of the ESA cement blend produced enhanced strength at 7.5 wt. % and 10 wt. % compared to control whereas, cement blended with 10 wt. % ESA produced a better 28-day flexural strength than control.

ACKNOWLEDGMENT

CONFLICT OF INTEREST

The authors declared that they have no conflict of interest.

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