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The Compressive Strength Indices of Calcined Clay-Cement Blended Concrete as a Function of Calcination and Cement Replacement Level Using Locally Sourced Clay

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Abstract:
Cement is highly valued primarily for its enhanced rate of hydration when compared to its predecessors. Its production process, however, is of adverse effects economically and mostly environmentally. Amidst the existing research routes for solving the problems associated with cement production, partial cement replaceability using sustainable supplementary cementitious materials appears to be gaining the most attention. However, the present research gap exists in the limited potential of the available materials in terms of availability or structural efficiency. As such, the abundance of local clay as well as its siliceous nature, in addition to the established structural properties of kaolinite (calcined Kaolin), suggests to the researchers that the index properties of clay, when properly optimized, could result in more efficient material with enhanced performance in concrete as a partial supplementary cementitious material. In the research, locally-sourced clay calcined at 450, 600, 750, and 900^{o}C were pulverized to pass through 150µm and used to replace Portland cement at 15%, 30%, 45%, and 60%. Results obtained indicated optimum calcination temperature for local clay to fall between 600 and 700^{o}C, yielding a compressive strength range of 15 – 22 MPA and 19 – 28MPA for 7 and 28 days, respectively. However, a more comprehensive range of cement replaceability was observed for clays calcined between 750 - 900^{o}C at a reduced mechanical index. As such, it is recommended that local clays be calcined between 600 and 700^{o}C, pulverized and sieved to pass through 150µm, and used to replace a maximum of 30% cement (by mass) for optimum efficiency and structural performance of calcined clay-cement blended concrete.

Keywords: *Calcination, locally sourced clay, siliceous materials, cement hydration, compressive strength*

1. Introduction

With the largest manufacturing volume, Portland cement (PC) is one of the most commonly utilized materials on the planet. However, its manufacture is associated with high energy consumption and significant CO_2 emissions globally, mainly during clinker production (Martirena, 2009), all representing severe sustainability concerns. One of the most comprehensive solutions to this problem is the use of Supplementary Cementitious Materials (SCM), which allows for the maintenance or even improvement of the mechanical qualities and durability of finished products, as well as improving environmental sustainability by reducing CO_2 emissions associated with clinker production (Martirena, 2009, Alujas, 2010, Escobar 2020). Between 1995 and 2014, there was a significant increase in worldwide cement output, which was seen as a standard response to fulfill the ever-increasing demand for cement-related structures to keep up with the growing population. However, worldwide cement production data shows no substantial variations in the amount of cement produced between 2015 and 2020. This is thought to be the outcome of the construction industry's integration of several supplementary cementitious materials (Statista, 2022).

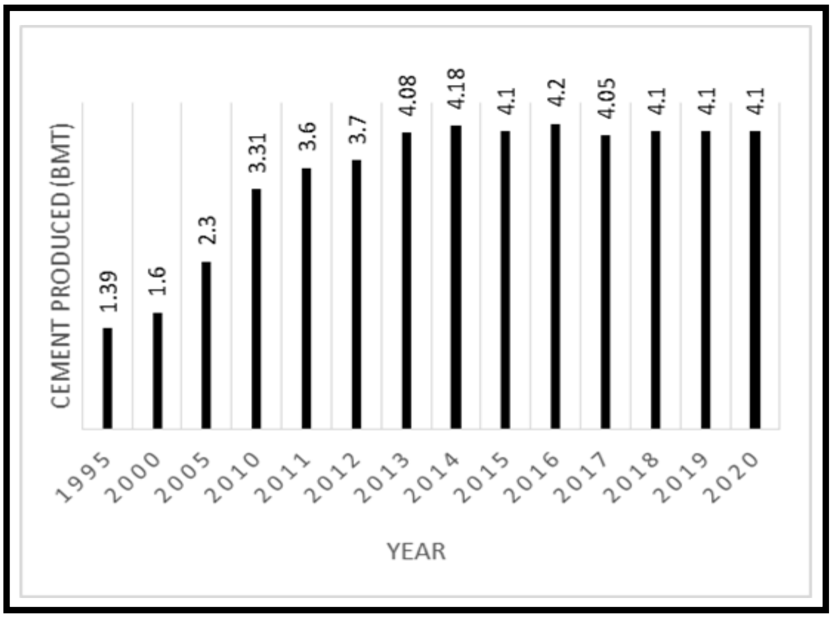

Figure 1: Global Cement Production Data (Statista, 2022)

Three major companies dominate the Nigerian cement sector, with Dangote Cement Plc leading the way with a market share of 60.6 percent and a local installed capacity of 29.3 million metric tonnes (MMT). Lafarge Africa Plc, with a manufacturing capacity of 10.5 MMT, owns 21.8 percent of the market, while BUA Group owns 17.6 percent. By establishing three-million-tonne-per-annum cement factories in Edo, Sokoto, and Adamawa, the BUA cement industry hopes to increase its output capacity from 11 million to 20 million tonnes per annum. Capacity will be increased by 9 million metric tons as a result of the additional developments. (Source: The Guardian, 2022). As a result, Nigeria's total cement production capacity is expected to reach 60 MMT by the end of 2022.

Approximately one kilogram of carbon dioxide is released for every kilogram of cement produced today (World Economic Forum, 2022). An average of 4 billion tons of cement and 4 billion tons of CO_2 are produced annually. This quantity is predicted to increase exponentially and mostly due to the logarithmic desire of developing natures to meet up with the rest of the world. Locally, it is estimated that the Nigerian cement sector emits roughly 60 million tons of carbon dioxide per year, and this figure is definitely going to rise in lockstep with the population.

A global issue is a development of sustainable solutions for decreasing energy use, carbon footprint, and cement production prices. As a result, current trends include energy efficiency (optimizing materials and processes associated with the production phase, such as switching from horizontal to vertical kilns (JRC 2013, EuLA 2012)); lower-carbon energy sources (such as switching from fossil fuels to gas or biomass (EuLA, 2014)); end-of-pipe solutions (Carbon Capture and Storage/Utilization, (TNO 2012, EuLA 2014, CEFIC 2013)); and carbonation (lime structures exhibit greater tendencies toward carbon; between 80 and 92 percent of carbon generated is reabsorbed in lime mortar constructions during a 100-year period, according to EESAC (2013)); and the use of Supplementary Cementitious Materials (SCMs). Researchers have paid a lot of attention to the use of supplementary cementitious materials, and they have mostly come to the same conclusion: 'The material is technically adequate but in short supply or the material is technically adequate only when used in a very small proportion as a cement replacement material.' A common example is ground granulated blast furnace slag, which has the potential to replace at least 60% of Portland cement without sacrificing strength but is in short supply, or a wide range of agriculturally related SCMs, which are relatively available but have limited performance potential in cement structures when used at higher proportions.

Because of their origin and material qualities, calcined clays have a strong chance of reducing clinker levels in cements (Zunino & Scrivener, 2020). Calcined clay, a mixture of clay minerals, can be used as a pozzolanic material instead of cement to reduce CO_2 emissions. The pozzolanic properties of metakaolin, the most widely used calcined clay, are well-known and extensively researched in the literature (Sabir et al., 2001). The presence of kaolinite, structural order, and physical characteristics influence the pozzolanic reaction in clays (Beuntner & Thienel, 2015). The features of thermally activated (calcined) clays are further influenced by process variables such as heat treatment, rate, and calciner environment (Slade & Jones, 1992). Clay has been used in concrete as a partial cement alternative as well as an additive (Beuntner and Thienel 2015, Okere and Sule 2019, Onwuka and Sule 2017, Onwuka et al. 2016, Shah et al. 2019, Orumu and Overo 2020, Jaskulski et al. 2020, Ottos and Daniel 2018, Zayed 2018). Increasing clay concentration reduces strength while improving environmental and durability indices in both scenarios.

CHEMICAL COMPOSITION		MINERAL COMPOSTION	
SiO_2	55 ± 2	Quartz	21 ± 2
Al_2O_3	25 ± 2	Illite	42 ± 2
Fe_2O_3	7 ± 2	Kaolinite	15 ± 2
CaO	4 ± 1	Chlorite	10 ± 2
K_2O	3.6 ± 0.5	Feldspar	5 ± 1
MgO	2.2 ± 0.2	Calcite	3 ± 1
TiO_2	1.2 ± 0.1		
SO_3	0.4 ± 0.1		
P_2O_5	0.3 ± 0.1		
NaO_2	0.1 ± 0.1		
MnO	0.1 ± 0.1		

Table 1: Mineral and Chemical Properties of Lias Delta Clay Thienel and Beuntner, 2012

Jaskulski et al. (2020) reviewed over 200 publications on clay's potential in the building industry. They asserted that the idea of replacing Portland cement with calcined clays was bolstered by clay's global distribution and its distinctive mineralogy. Furthermore, it has been proven that this form of pozzolanic material can be utilized as a clinker/cement substitute or as supplemental cementitious material to meet the global demand to reduce CO_2 emissions in concrete technology while remaining environmentally and economically sound.

2. Materials and Methods

Cube specimens were cast and tested in compression to study the compressive strength indices of calcined clay blended cement concrete. The concrete mixtures incorporated river sand as fine aggregate, granite as coarse aggregate, calcinated and pulverized clay under variable temperature conditions as a partial replacement for cement, and water-to-cementitious (W/cm) material ratios were taken to be 0.50. The clay was sourced and harvested in the Niger Delta University environs and at a depth exceeding 0.5m from natural ground level. The clay samples were air-dried and calcinated at 450, 600, 750, and 900oC, pulverized to pass through a 150μm sieve, and used to replace Portland cement (by mass) in a grade M15 concrete. In addition, 3 cubes per batch were produced to be tested at ages 7 and 28 days, and average results were taken.

Figure 2: Harvesting of Clay Samples

Figure 3: Calcination of Clay Samples

Figure 4: Mixing and Production of Cube Specimens

2.1. Concrete Production

The concrete mix was batched by weight nominally using the ratios of grade M20. Information for the mix ratio and masses used in the concrete production are available in Table 2.

	Mix Ratio Information				Weight Batching Information				
C.R. L	Cement	Clay	Sand	Granite	Clay	Cement	Sand	Granite	W/C
Control	1	0	2	4	0	7.185	14.375	28.75	3.5925
15	0.15	0.85	2	4	1.0775	6.1075	14.375	28.75	3.5925
30	0.3	0.7	2	4	2.155	5.03	14.375	28.75	3.5925
45	0.45	0.55	2	4	3.2325	3.9525	14.375	28.75	3.5925
60	0.6	0.4	2	4	4.3125	2.875	14.375	28.75	3.5925

Table 2: Mix Ratio and Batching Information

2.2. Experimental Standards and Research Factorials

The standard methodology, involved in this research, as well as research factorials, is treated as contained in Table 3 below:

S/N	Test Type	Test STD	Repl. Level	Temp. levels	Test Age	Spec. per age	Control specimen	Total Specimen
			B	C	D	E	F	(A*B*C*D*E) +F
1	Particle Size Distribution for Fine Aggregate	BS 812 -103 (1985)	-	-	-	-	-	-
2	Particle Size Distribution for Coarse Aggregate	BS 812 -103 (1985)	-	-	-	-	-	-
4	Specific Gravity	BS 4450-3; (1978)	-	4	-	-	1	5
6	Compressive Strength	BSEN 12390- 3	4	4	2	3	6	102

Table 3: Experimental Sample/Specimen Production Summary

3. Results and Discussions

3.1. Particle Size Distribution

The particle size distribution for the aggregates is shown in figures 5 and 6. Results indicate that the fine aggregate is well-graded sand of type zone 3 and structurally suitable for concrete production. Coarse aggregate was observed to have its maximum grain diameter be less than 25.4mm; it was also observed to be well-graded and suitable for concrete production.

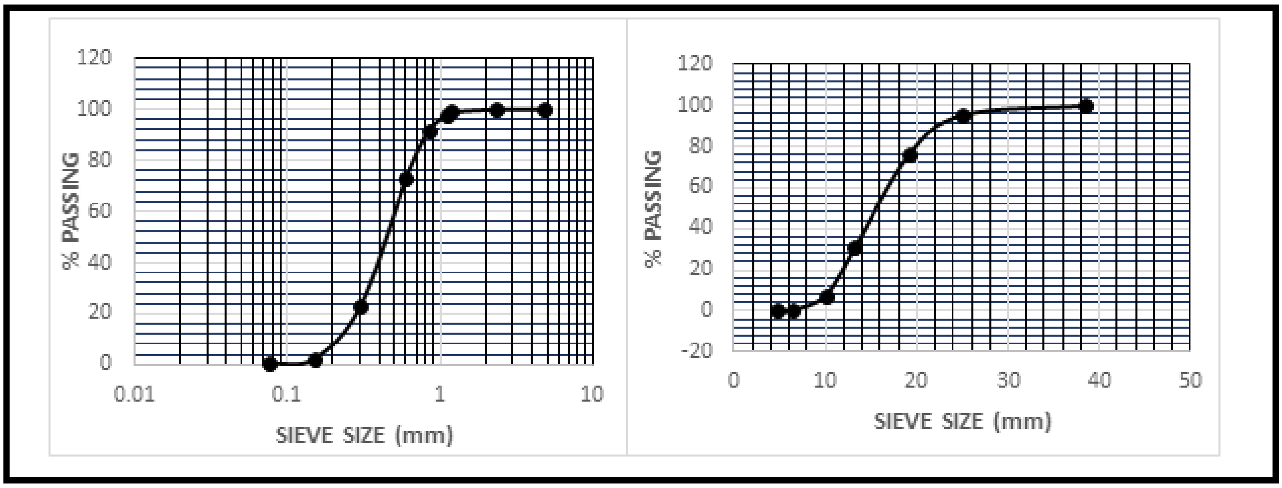

Figure 5: Particle Size Distribution for Fine Aggregate (Left) and Coarse Aggregate (Right)

3.2. Specific Gravity

The ratio of the weight of soil to the weight of water of identical volume is known as specific gravity. Due to the presence of confined voids in clay soil, it shrinks and swells. Clay's density and specific gravity are reduced due to these voids. It is believed that trapped air will be released during calcination, improving specific gravity. However, this depends on the material behaviour under heat, as it is also scientific that most materials expand under heat and tend to reduce mass relative to increased volumes. Specific gravity results show that Portland cement has a specific gravity of 3.13, which is observed to be greater than that of calcined clay measured at 2.31, 2.33, 2.31, and 2.35 at calcination temperatures 450, 600, 750, and 900^{o}C, respectively. A small amplitude quadratic curve was observed for the specific gravities of the calcined clay samples relative to increasing calcination temperature. The optimum specific gravity of 2.33 was observed at a calcination temperature of 600^{o}C.

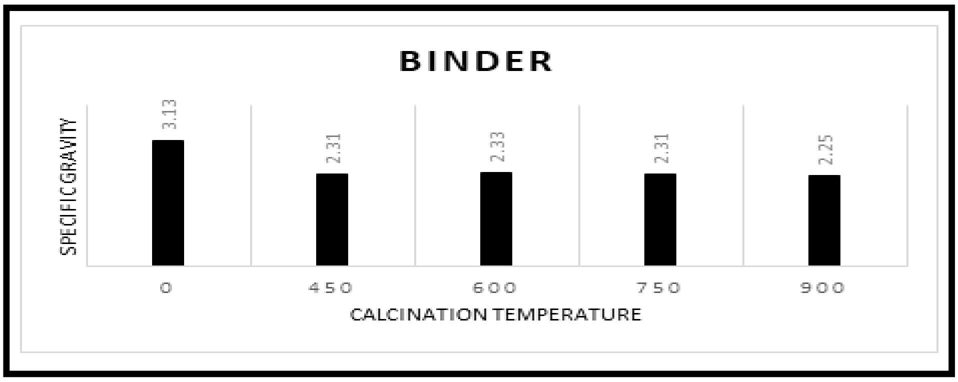

Figure 6: Specific Gravity of Calcined Clay Relative to Calcination Temperature

3.3. Compressive Strength

The compressive strength result indicates a need for controlled calcination of calcined clay in lieu of reaching the clay's optimal performance in concrete as a partial cementitious material.

Code	Temp (oC)	Cement Rep. L	7 Days Loading				7D σ	28 Days Loading				28D σ		ASTM C-618 (2012) Check
			P1	P2	P3	AP	N/mm²	P1	P2	P3	AP	N/mm²	SAI (%)	
AA	CTRL		430	430	440	433.33	19.26	520	520	520	520.00	23.11	100.00	Yes
B1	450	15%	590	365	350	435.00	19.33	465	500	525	496.67	22.07	95.51	Yes
B2		30%	215	260	250	241.67	10.74	275	315	305	298.33	13.26	57.37	NO
B3		45%	275	270	240	261.67	11.63	280	255	255	263.33	11.70	50.64	NO
B4		60%	155	150	145	150.00	6.67	170	145	150	155.00	6.89	29.81	NO
C1	600	15%	440	540	545	508.33	22.59	645	635	655	645.00	28.67	124.04	YES
C2		30%	530	345	215	363.33	16.15	450	425	430	435.00	19.33	83.65	YES
C3		45%	215	235	220	223.33	9.93	270	270	275	271.67	12.07	52.24	NO
C4		60%	155	140	180	158.33	7.04	165	170	170	168.33	7.48	32.37	NO
D1	750	15%	340	375	265	326.67	14.52	425	420	450	431.67	19.19	83.01	YES
D2		30%	460	235	360	351.67	15.63	400	425	430	418.33	18.59	80.45	YES
D3		45%	375	415	350	380.00	16.89	350	415	375	380.00	16.89	73.08	NO
D4		60%	280	275	350	301.67	13.41	250	245	320	271.67	12.07	52.24	NO
E1	900	15%	210	215	200	208.33	9.26	345	355	415	371.67	16.52	71.47	NO
E2		30%	250	210	265	241.67	10.74	350	300	165	271.67	12.07	52.24	NO
E3		45%	245	185	255	228.33	10.15	250	235	245	243.33	10.81	46.79	NO
E4		60%	245	215	180	213.33	9.48	235	245	185	221.67	9.85	42.63	NO

Table 4: Summary of Compressive Strength Indices for Calcined Clay-Cement Blended Concrete

Calc. Temp	7-Day Strength Results						28-Day Strength Results				
	0	15	30	45	60		0	15	30	45	60
Control	19.26						23.11				
450		19.33	10.74	11.63	6.67			22.07	13.26	11.70	6.89
600		22.59	16.15	9.93	7.04			28.67	19.33	12.07	7.48
750		14.52	15.63	16.89	13.41			19.19	18.59	16.89	12.07
900		9.26	10.74	10.15	9.48			16.52	12.07	10.81	9.85

Table 5: Summary of Compressive Strength Indices for Calcined Clay-Cement Blended Concrete

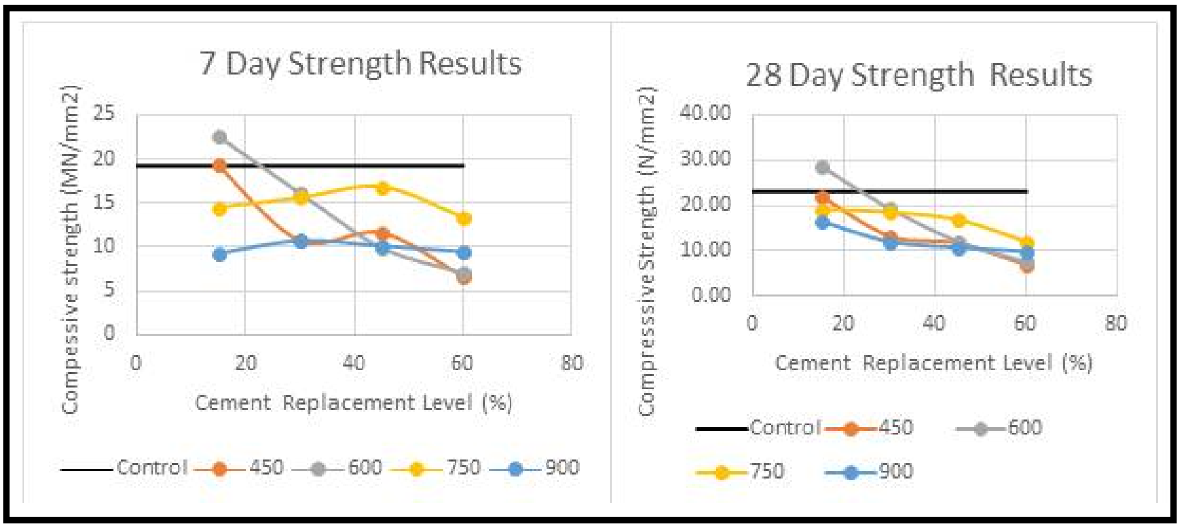

Figure 7: Summary of Compressive Strength Indices for Calcined Clay-Cement Blended Concrete at 7 and 28 days

ASTM C-618 (2012) recommends, amongst others, that the integration of supplementary cementitious materials (SCM) as partial cement alternatives be on 75% strength activity index criteria, such that concrete containing SCMs or pozzolans must demonstrate the ability to structurally match up at least 75% of the 28-day compressive strength control cement specimen, regardless of production variables. In this regard, as shown in Table 4, specimens B1, C1, C2, D1, and D2 were observed to satisfy this requirement and can be integrated into concrete production as partial replacements for cement. Summarised results shown in Figure 7 indicate a general reduction in compressive strength of calcined-clay cement relative to an increase in cement replacement level. At 15% cement replacement level, clay samples produced at

600°C showed greater efficiency in strength contribution to the concrete mix, having a compressive strength of 28.67N/mm^2, and being 24% greater than the control of 23.11N/mm^2. At 750°C, 28day strength results were 19.19, 18.59, 16.89, and 12.07N/mm2 for 15, 30, 45, and 60% cement replacement levels, respectively, indicating a steady reduction in strength relative to a reduction in cement proportion. Similar results were obtained for samples produced at 900°C. No significant slope in compressive strength was observed between the respective cement replacement levels with samples produced at 750°C and 900°C. This indicates the contribution that at higher temperatures, a greater proportion of the calcined clay is technically allowed with no extra deficiency in the compressive strength indices. However, these are seen to yield results between 10N/mm^2 and 19N/mm^2 for a replacement range of 30 – 45%.

From figure 7, a target compressive strength of the control can be achieved at a cement replacement level of approximately 23% using calcined clay calcinated at a minimum calcination temperature of 600°C. This is novel and promises to reduce the economic and adverse environmental effects of cement production.

4. Conclusion and Recommendation

From the above, the following concludes the findings of the research exercise:

- Locally sourced clay can be effectively used as a cement replacement material when calcined optimally.
- The proportion of cement to be replaced by calcined clay depends primarily on the structural use of the concrete, as well as the calcination temperature.
- Optimum temperature for calcination of local clay ranges between 600 – 700°C, relative to the optimal strength performance of calcined clay-cement blended concrete.
- At 23% cement replacement level, local clay calcined at a minimum calcination temperature of 600°C holds promise to produce a calcined clay-cement blended concrete with no structural deficit in compressive strength.
- It is recommended that further investigation on the durability indices of calcined clay-cement blended concrete be studied to further inform the engineering society on a more holistic view towards integrating locally sourced clay into the construction industry as a partial replacement for Portland cement.

5. Acknowledgment

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6. Conflict of Interest

We, the authors of this article titled 'The Compressive Strength Indices of Calcined Clay-Cement Blended Concrete as a Function of Calcination and Cement Replacement Level Using Locally Sourced Clay', here-in state that we are not in any conflict of interest, be it financial or otherwise with ourselves or with any external third party. We hereby affirm the absence of any conflicting interest relating to the production and publication of this article.

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