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Valorization of a Low-Kaolinite Clay for Use in Low-Carbon Cement Formulations: Mathematical Modelling of Mechanical Properties Using Mixture Designs

Mame Arame Ousmane Ndiaye[1], Mamadou Moustapha Diouf[2*], Alpha Ousmane Toure[2], Mouhamadou Bachir Lo[3], Mamadou Faye[2], Mamadou Ngom[4], Mamadou Senghor[4], Farba Bouyagui Tamboura[1,5]

[1]Department of Chemistry, UFR SATIC, Alioune Diop University of Bambey (UADB), Bambey, Senegal
[2]Water, Energy, Environment and Industrial Processes Laboratory (LE3PI), Ecole Supérieure Polytechnique (ESP), Cheikh Anta Diop University of Dakar (UCAD), Dakar, Senegal
[3]Project Management Office, Dangote Cement Senegal S.A., Pout, Senegal
[4]Quality Department, Dangote Cement Senegal S.A., Pout, Senegal
[5]Inorganic and Organic Materials Chemistry Team (ECMIO), Department of Chemistry, UFR SATIC, Alioune Diop University of Bambey (UADB), Bambey, Senegal
Email: *mamadoumoustapha4.diouf@ucad.edu.sn

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Abstract

In response to the climate challenge, the cement industry is seeking to reduce CO_2 emissions associated with clinker production. This study investigates the formulation of low-carbon LC3 cements using a binary clay blending strategy that combines a highly reactive clay (70% kaolinite) with a local clay containing only 2.6% kaolinite. A mixture design methodology was applied to develop and optimize formulations with 40% and 50% clinker, incorporating calcined clays, limestone, and phosphogypsum. The results demonstrate the technical feasibility of producing LC3 cements that meet standard strength classes. In 50% clinker formulations, incorporating up to 13.2% of the low-kaolinite clay yields a 42.5 N cement, with profit margins between 23330.9 and 23528.9 CFA francs per ton. Similarly, incorporating up to 27.2% of low-kaolinite clay results in a 32.5 R cement, with profit margins ranging from 23330.9 to 23738.9 CFA francs per ton for 50% clinker formulations, and from 29844.8 to 29945.3 CFA francs per ton for 40% clinker formulations. Overall, this binary clay blending approach offers a sustainable, economically attractive, and innovative pathway for decarbonizing the African cement industry.

Keywords

Low-Carbon Cement (LC3), Clay, Kaolinite, Compressive Strength, CO_2 Emissions

1. Introduction

The cement industry poses a major challenge for climate change mitigation, as its emissions from clinker production account for approximately 8% of global greenhouse gas emissions [1]. This carbon footprint stems primarily from the decarbonation of limestone during clinkerization [2], an energy-intensive and polluting process that also generates dust, nitrogen oxides (NOx), sulfur oxides (SOx), and other environmental impacts such as soil erosion and water pollution [3]. The building sector accounts for 30% of global carbon emissions [4].

In this context, the development of innovative low-carbon binders, such as Limestone Calcined Clay Cement (LC3), stands out as an essential solution. While conventional Portland cement (CEM I) typically contains 95% to 100% clinker, with up to 5% minor constituents [5], the standard LC3 formulation significantly reduces the clinker content by incorporating approximately 50% Portland clinker, 30% calcined clay, 15% finely ground limestone, and 5% gypsum [3] [6]. This system leverages the synergistic pozzolanic (formation of C-A-S-H) and carboaluminate reactions to improve mechanical strength and durability while reducing porosity [7]-[9].

Although such substitution reduces the carbon footprint by 30% to 40% compared to traditional Portland cements [10], the efficiency of these conventional formulations generally relies on the exclusive use of kaolinite-rich clays, which are well-known for their high pozzolanic reactivity after thermal activation. The present study distinguishes itself from this conventional approach by evaluating the integration of a low-kaolinite clay into the LC3 cement formulation. It is important, however, to emphasize that this low-grade resource is not evaluated as a standalone precursor, but is instead utilized within a binary blend with a highly reactive clay. The technical feasibility demonstrated in this work fundamentally depends on this combined formulation strategy, which aims to valorize previously underutilized low-kaolinite clays to expand the application potential of these low-carbon binders. This study fits within a circular economy framework, assessing the feasibility of using this local binary clay system to produce LC3 cements. The specific objectives include:

- formulating low-carbon cements using optimized combinations of high- and low-kaolinite clays;
- modeling of mechanical strengths at 2, 7, and 28 days;
- optimizing the binary clay blend dosage to satisfy the requirements of strength classes 32.5 R and 42.5 N.

By valorizing underutilized local resources through appropriate blending strategies, this research aims to accelerate the decarbonization of the cement industry in the African context. To this end, a methodological approach based on mixture designs, processed using Design Expert software, was adopted.

2. Materials and Methods

2.1. Raw Materials

The various raw materials used in the formulation of the binders were obtained from different sources: clinker was supplied by Ciments et Matériaux du Mali (CMM SA), phosphogypsum was provided by Industries Chimiques du Sénégal (ICS, Senegal), limestone and Clay 2 were collected from the Thiès region (Senegal), while Clay 1 was sourced from Kédougou (Senegal). The chemical composition of these materials in terms of oxides was determined by XRF analysis (ARL 9900). At the same time, the loss on ignition (L.O.I) was quantified by heat treatment of the samples at 950˚C for 30 minutes in a muffle furnace (Nabertherm). This value is calculated using Equation (1).

$$\text{L.O.I}(\%) = \frac{m_2 - m_3}{m_1} \times 100 \quad (1)$$

where:

m_1 is the initial mass of the dry sample before heat treatment.

m_2 is the mass of the crucible plus the sample before calcination in the furnace.

m_3 is the mass of the crucible plus the sample after heating at 950˚C for 30 minutes.

The oxide contents and loss on ignition of the raw materials are shown in Table 1.

Table 1. Oxide composition and loss on ignition of the various raw materials.

Components (%)	Raw materials				
	Clay 1	Clay 2	Limestone	Clinker	Phosphogypsum
SiO_2	41.93	81.75	3.19	21.46	8.82
Al_2O_3	30.17	8.39	0.91	4.65	0.35
Fe_2O_3	4.26	3.72	0.38	4.96	0.05
CaO	2.77	0.42	53.27	65.55	38.12
MgO	0.45	0.72	0.72	0.97	0.38
P_2O_5	0.09	0	0.12	0.2	0.83
Na_2O	0.03	0.06	0.43	0.5	0.03
K_2O	0.01	0.33	0.03	0.16	0.04
SO_3	0.06	0.24	0.04	0.83	53.05
Cl	0.012	0.039	---	0.016	---
LOI	14.59	3.6	42.2	5.62	---

The kaolinite content of the samples was determined by thermogravimetric analysis (ELTRA THERMOSTEP). The values obtained were 70% for Clay 1 and 2.6% for Clay 2. This assessment is based on the analysis of mass losses at 500˚C ($L.O.I_{500^\circ C}$) and 850˚C ($L.O.I_{850^\circ C}$), identified on the thermograms in Figure 1 and Figure 2, in accordance with Equation (2).

$$\text{kaolinite}(\%) = \frac{\left(L.O.I_{850^\circ C}\right) - \left(L.O.I_{500^\circ C}\right)}{0.14} \tag{2}$$

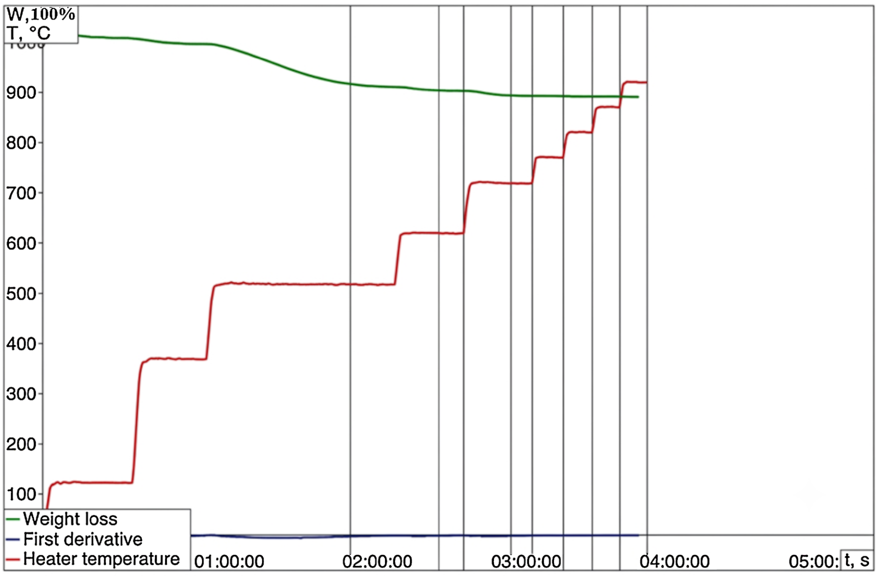

Figure 1. Thermogravimetric curve of clay 1.

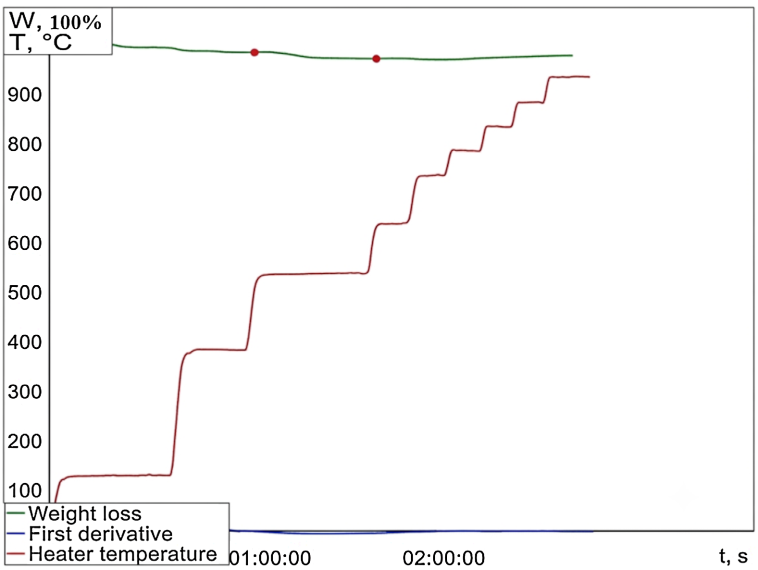

Figure 2. Thermogravimetric curve of clay 2.

Initially, the materials underwent primary crushing using a jaw crusher (PE60X100). They were then dried in an oven at a temperature of 110˚C for 3 hours to remove any residual moisture. Finally, a grinding stage was carried out using a ball mill (SM500).

This series of operations aims to increase the fineness of the particles, thereby increasing their specific surface area.

The clays were also calcined at a temperature of 850˚C for two hours. This process is designed to dehydroxylate the kaolinite $Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$ and disrupt its crystalline structure. This heat treatment produces metakaolin with the chemical formula $Al_2O_3{\cdot}2SiO_2$, an amorphous aluminosilicate with high pozzolanic reactivity. Equation 3 illustrates this transformation.

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O \tag{3}$$

2.2. Binders Formulation Methods

The formulation process for the various binders is illustrated in **Figure 3**. The methodology involved preparing two series of mixtures incorporating various proportions of clinker, limestone and the two types of clay (Clay 1 and Clay 2). To ensure consistent setting, the phosphogypsum content was kept constant at 2.8% for all preparations. Each mixing unit has been designed to handle a total mass of 450 g.

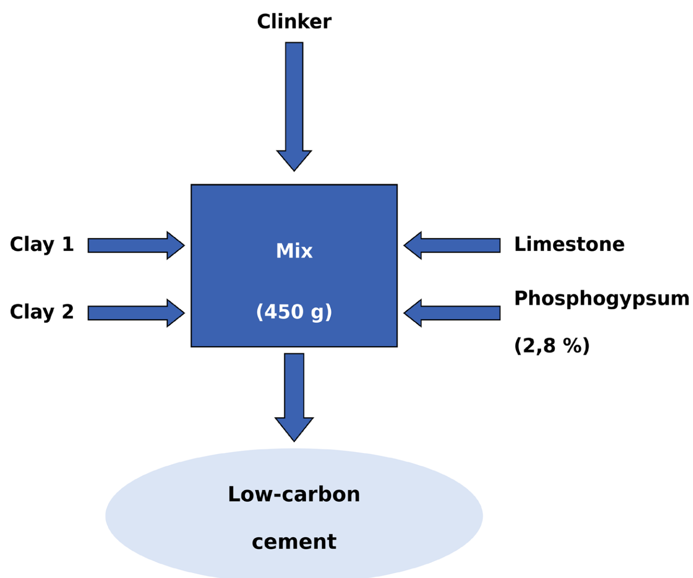

Figure 3. Low-carbon cement formulation method.

2.2.1. First Series of Mixtures

This first series of mixtures was produced by setting the clinker content at 50% (the minimum threshold generally required for LC3 cements) and the limestone content at 20%, whilst varying the percentages of the two clays.

The design of experiments method, specifically mixture designs, was employed. The high (maximum values) and low (minimum values) levels of each factor (percentage of clay 1 and clay 2) are listed in **Table 2**. The response variables studied are the mechanical strengths at 2, 7 and 28 days.

Table 2. Level of factors.

Level	Clay 1 (%)	Clay 2 (%)
Low level	0	0
Top level	27.2	27.2

The Design Expert software was used to generate the design of experiments matrix (Table 3) and to perform statistical analysis of the results. This matrix defines the specific list of combinations to be tested, enabling the formulation space to be explored optimally with a reduced number of trials.

Table 3. Experiment matrix for the first series of mixtures.

Formulations	Clay 1 (%)	Clay 2 (%)
F50-1.1	27.2	0
F50-1.2	27.2	0
F50-2	20.4	6.8
F50-3.1	13.6	13.6
F50-3.2	13.6	13.6
F50-4	6.8	20.4
F50-5.1	0	27.2
F50-5.2	0	27.2

The integration of replicate points within the experimental matrix is indispensable for estimating pure experimental error, thereby allowing the quantification of true performance variations against handling variability.

2.2.2. Second Series of Mixtures

This series is characterised by a clinker content below the minimum value generally required (50%). This approach is motivated by the desire to further reduce the carbon footprint. The clinker content was set at 40% and the limestone content at 30%, whilst varying the percentages of the two clays. Adopting the same approach as for the first series of mixtures, the mixture design method was used with the Design Expert software. The high and low levels of each factor (clay 1 and clay 2 percentages) and the treatments used were retained. Consequently, an experimental design identical to that of the first series was obtained (Table 4).

2.3. Compression Testing of Mortar

The experimental setup utilized a TYE-600B compression testing machine (Figure 4), equipped with a constant-rate load controller and a data acquisition system ensuring measurement accuracy up to failure. In accordance with the EN 196-1 standard [11], each mortar was prepared with a water-to-binder ratio of 0.50 and a binder-to-sand ratio of 1:3 by mass, corresponding to 450 g of the formulated

Table 4. Experiment matrix for the second series of mixtures.

Formulations	Clay 1 (%)	Clay 2 (%)
F40-1.1	27.2	0
F40-1.2	27.2	0
F40-2	20.4	6.8
F40-3.1	13.6	13.6
F40-3.2	13.6	13.6
F40-4	6.8	20.4
F40-5.1	0	27.2
F40-5.2	0	27.2

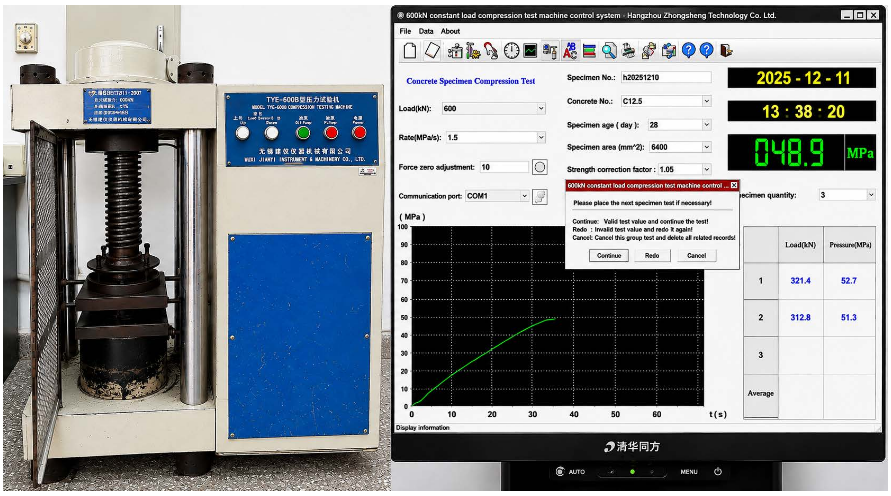

Figure 4. Compressive strength testing equipment (TYE-600B) and data acquisition software interface.

binder, 1350 g of standardized quartz sand, and 225 g of water per batch. The resulting mortar was poured in two layers into prismatic moulds to produce standard 40 mm × 40 mm × 160 mm specimens, with each layer compacted by 60 blows using a shock table. After levelling, the specimens were left in their moulds and placed in a climatic chamber for initial curing. After 24 hours, they were demoulded and immersed in curing tanks containing water maintained at (20 ± 1)˚C until the testing ages of 2, 7, and 28 days. The mechanical strengths were measured at these ages in order to follow the evolution of early-age (2 days) and intermediate-age (7 days) strength, as well as the reference age, 28 days, which is the conventional benchmark used for cement classification [5] [11].

For each formulation, three prismatic specimens were prepared at the time of casting, and one specimen was subjected to destructive testing at each curing age.

2.4. Financial Impact

The aim is to assess the profit generated per ton of LC3 cement produced.

Table 5 sets out the costs of raw materials based on data from a local cement plant.

Table 5. Raw material cost per ton.

Raw materials	Prices (FCFA)/ton
Clinker	68,139
Limestone	3000
Clay 1	6000
Clay 2	4500
Phosphogypsum	10,500

The profit per ton of cement produced can then be calculated using Equation (4).

$$B = P - Q\left(X_1 + X_2\right) - \sum X_i \cdot C_i \quad (4)$$

where:

- P = 63,000 CFA francs is the selling price of a ton of cement;
- C_i and X_i represent, respectively, the cost per ton and the content of each constituent of the optimised cement, where the index denotes: i = 1 for clay 1, i = 2 for clay 2, i = 3 for phosphogypsum and i = 4 for clinker;
- Q = 15,000 CFA francs: the cost of calcining one ton of clay (estimated value).

3. Results and Discussion

3.1. Experimental Results

The development of the compressive strengths of the mortars formulated for the two series of mixtures (50% and 40% clinker) is recorded in Table 6 and Table 7. A cross-analysis of these data highlights a dual dependence on both the clinker substitution rate and the mineralogical quality of the clay.

On the one hand, the results show that, for all the test durations (2, 7 and 28 days), the compressive strength at 50% clinker consistently exceeds that obtained at 40%. This trend can be explained by the reduction in the clinker content, which mechanically limits the availability of calcium silicates, phases essential for the

Table 6. Compressive strengths at 2 days (R-2d), 7 days (R-7d) and 28 days (R-28d) for the first batch of the mixture.

Formulations	% Clay 1	% Clay 2	R-2d (MPa)	R-7d (MPa)	R-28d (MPa)
F50-1.1	27.2	0	18.9	43.2	51.5
F50-1.2	27.2	0	18	44.6	52.9
F50-2	20.4	6.8	15.5	38	51.3
F50-3.1	13.6	13.6	15.8	38.5	39
F50-3.2	13.6	13.6	14.2	37.3	40.8
F50-4	6.8	20.4	13.9	31.7	36.6
F50-5.1	0	27.2	12.2	25.1	33
F50-5.2	0	27.2	12.3	25.9	34.3

Table 7. Compressive strengths at 2 days (R-2d), 7 days (R-7d) and 28 days (R-28d) for the second batch of the mixture.

Formulations	% Clay 1	% Clay 2	R-2d (MPa)	R-7d (MPa)	R-28d (MPa)
F40-1.1	27.2	0	12.3	31	38.2
F40-1.2	27.2	0	12.4	31.1	38.3
F40-2	20.4	6.8	9.7	28.8	34.5
F40-3.1	13.6	13.6	8.1	23.7	31.9
F40-3.2	13.6	13.6	8.5	24.2	32
F40-4	6.8	20.4	7.5	19	28.7
F40-5.1	0	27.2	6.83	15	22.9
F40-5.2	0	27.2	6.67	15.4	23.6

formation of the initial C-S-H skeleton during primary hydration.

Furthermore, mechanical performance appears to be closely linked to the type of clay used. Regardless of the mortar's age, the highest strength is achieved when using Clay 1 alone, whilst the lowest values are obtained when using only Clay 2. This disparity highlights the superior reactivity of Clay 1. In the case of binary clay mixtures, increasing the proportion of Clay 2 leads to a gradual decrease in strength, confirming its inferior quality. This phenomenon is directly linked to the low kaolinite content of Clay 2; its inclusion reduces the overall reactive fraction of the system, thereby leading to a decline in performance. This direct relationship between kaolinite content and the development of mechanical strength is fully consistent with the findings of Avet and Scrivener [12].

This mineralogical reactivity results in a particularly efficient hardening kinetics, enabling the LC3 system to develop remarkable early strength. As early as 2 days, the values range between 12.2 and 18.9 MPa for the 50% clinker series, thereby surpassing the conventional performance of cements based on natural pozzolan, which often struggle to reach such levels in the short term [13].

Between 2 and 7 days, a significant rate of increase (often exceeding 100%) is observed. This phase of intense growth reflects rapid pozzolanic activity and hydration kinetics from the very first days. These results are consistent with the work of Zunino *et al.* [14], who demonstrate that the structuring of the cement matrix in ternary cements occurs predominantly during the first week.

At 28 days, although the rate of growth is moderate, strengths of over 50 MPa are observed for the formulation containing 50% clinker, demonstrating that LC3-50 can match or exceed the performance of ordinary Portland cement thanks to a refinement of porosity and densification of the C-S-H matrix, in line with the work of Dhandapani *et al.* [15].

3.2. Mathematical Modelling

It is essential to select the most appropriate model to accurately map the relationship between a given response (R-2d, R-7d, R-28d) and the factors (% clay 1 and %

clay 2). The optimal model is selected when its sequential p-value is below 5% ($p < 0.05$), indicating that a higher-order model provides a significant improvement in predictive capacity, while exhibiting a high R^2-predicted value (close to 1) that is in good agreement with its R^2-ajusted [16] [17]. Finally, the overall model adequacy is confirmed if the p-value of the Lack of Fit test is greater than 0.05 (or 5%), thereby indicating that the model provides an adequate representation of the experimental data [18].

On this basis, the sequential analysis of the different models (linear, quadratic, and cubic) shows that the linear model is best suited to modelling the 2-day, 7-day, and 28-day strengths of the first series of mixtures (**Table 8**). Conversely, for the second series of mixtures, the quadratic model proves to be the most effective for the 2-day strength, whilst the 7-day and 28-day strengths are better described by the cubic model (**Table 9**).

The selected models were fitted, and the resulting predictive equations are presented in **Table 10**.

The models are supported by robust statistical indicators (**Table 11** and **Table 12**), with p-values below 5%, a coefficient of determination close to 1, and an adjusted coefficient likewise near 1. These elements show that the regressions are statistically reliable and explain most of the variability observed in the data; these remarks confirm that these models satisfactorily reproduce the experimental results [16]-[18].

Table 8. The various mathematical models in the first series of mixtures (n = 8).

Source	Statistical analysis R-2d				
	Degrees of freedom	Sequential p-value	Lack of fit p-value	R^2-ajusted	R^2-predicted
Linear	1	0.0002	0.5194	0.9089	0.8736
Quadratic	1	0.4417	0.4499	0.9041	0.8442
Cubic	1	0.2183	0.6036	0.9217	0.8627
Source	**Statistical analysis R-7d**				
	Degrees of freedom	Sequential p-value	Lack of fit p-value	R^2-ajusted	R^2-predicted
Linear	1	<0.0001	0.0503	0.9357	0.9134
Quadratic	1	0.1189	0.0681	0.9548	0.9316
Cubic	1	0.2524	0.0545	0.9610	0.8600
Source	**Statistical analysis R-28d**				
	Degrees of freedom	Sequential p-value	Lack of fit p-value	R^2-ajusted	R^2-predicted
Linear	1	0.0001	0.0510	0.9140	0.8881
Quadratic	1	0.4136	0.0386	0.9110	0.8700
Cubic	1	0.1548	0.0411	0.9370	0.7700

Table 9. The various mathematical models in the second series of mixtures (n = 8).

Source	Degrees of freedom	Sequential p-value	Lack of fit p-value	R^2-adjusted	R^2-predicted
	Statistical analysis R-2d				
Linear	1	0.0001	0.0112	0.9113	0.8627
Quadratic	1	0.0009	0.2334	0.9901	0.9849
Cubic	1	0.0629	0.9431	0.9953	0.9932
	Statistical analysis R-7d				
Source	**Degrees of freedom**	**Sequential p-value**	**Lack of fit p-value**	**R^2-adjusted**	**R^2-predicted**
Linear	1	<0.0001	0.03	0.9881	0.9826
Quadratic	1	0.1215	0.0397	0.9916	0.9878
Cubic	1	0.007	0.5555	0.9986	0.9972
	Statistical analysis R-28d				
Source	**Degrees of freedom**	**Sequential p-value**	**Lack of fit p-value**	**R^2-adjusted**	**R^2-predicted**
Linear	1	<0.0001	0.0293	0.982	0.9727
Quadratic	1	0.0437	0.0672	0.9912	0.9861
Cubic	1	0.0111	0.8599	0.9982	0.9958

Table 10. Mathematical models predicting compressive strength (R in MPa) for the two series of mixtures.

Due date	First series	Second series
2 days	$R_{2d} = 0.663X_1 + 0.447X_2$	$R_{2d} = 0.452X_1 + 0.251X_2 - 0.007(X_1X_2)$
7 days	$R_{7d} = 1.633X_1 + 0.980X_2$	$R_{7d} = 1.142X_1 + 0.559X_2 + 5\times10^{-3}(X_1X_2) + 5\times10^{-4}X_1X_2(X_1 - X_2)$
28 days	$R_{28d} = 1.923X_1 + 1.197X_2$	$R_{28d} = 1.406X_1 + 0.855X_2 + 6\times10^{-3}(X_1X_2) - 5\times10^{-4}X_1X_2(X_1 - X_2)$

Table 11. Analysis of variance for the models in the first mixture series (n = 8).

Source/Statistics	R-2d	R-7d	R-28d
	Degrees of freedom		
model	1	1	1
Lack of fit	3	3	3
Pure Error	3	3	3
	p-values		
Model (overall)	0.0002	0.0003	0.0001
Linear	0.0002	<0.0001	0.0001
Lack of fit	0.5194	---	0.0510

Continued

Summary of the adjustment			
R^2	0.9219	0.9449	0.9263
R^2-ajusted	0.9089	0.9357	0.9140
R^2-predicted	0.8736	0.9134	0.8881
Adequate precision	15.8694	4	16.3761

Table 12. Analysis of variance for the models in the second mixture series (n = 8).

Source/Statistics	R-2d	R-7d	R-28d
Degrees of freedom			
model	2	3	3
Lack of fit	2	1	1
Pure Error	3	3	3
p-values			
Model (overall)	<0.0001	<0.0001	<0.0001
Linear	<0.0001	<0.0001	<0.0001
X_1X_2	0.0009	0.0103	0.0042
$X_1X_2(X_1 - X_2)$	---	0.007	0.0111
Lack of fit	0.2334	0.5555	0.8599
Summary of the adjustment			
R^2	0.9929	0.9992	0.9989
R^2-ajusted	0.9901	0.9986	0.9982
R^2-predicted	0.9849	0.9972	0.9958
Adequate precision	39.2994	91.3888	83.5047

The use of predictive mathematical models yielded. Figure 5, which presents a comparison between the two mix designs. This confirms the dominant influence of the clinker content, as the strengths obtained with a 50% clinker content exceed those obtained with a 40% clinker content. Furthermore, the drop in strength following the increase in clay 2 confirms the detrimental effect of clay 2 on the overall reactivity of the system. This phenomenon, which is directly linked to the low kaolinite content of Clay 2 (2.6% compared to 70% for Clay 1), thus confirms the critical importance of the mineralogical quality of clays in the formulation of LC3 cements.

3.3. Formulation Range for Cement of Strength Classes 32.5 R and 42.5 N

Cements of classes 32.5 R and 42.5 N are the most widely used types of cement on the market. The specified strength limits for these cement classes are listed in Table 13.

Figure 6 and Figure 7 illustrate the various mixture combinations used to

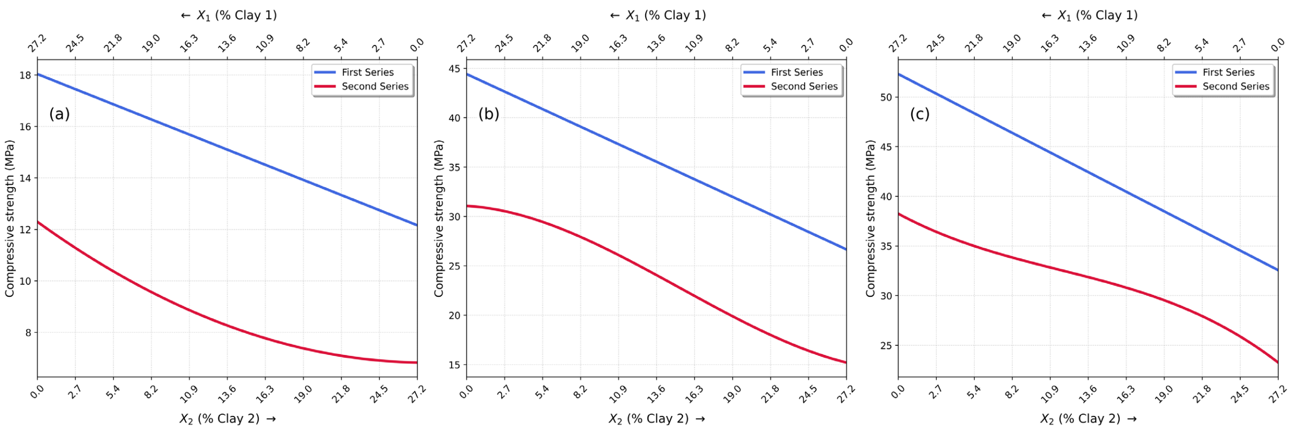

Figure 5. Compressive strength development as a function of clay content: (a) 2 days; (b) 7 days; (c) 28 days.

Table 13. Minimum and maximum limits of the compressive strength of Class 32.5 R and 42.5 N cements.

Strength	32.5 R strength class		42.5 N strength class	
	Minimum	Maximum	Minimum	Maximum
2-day strength (MPa)	10	---	10	---
28-day strength (MPa)	32.5	52.5	42.5	62.5

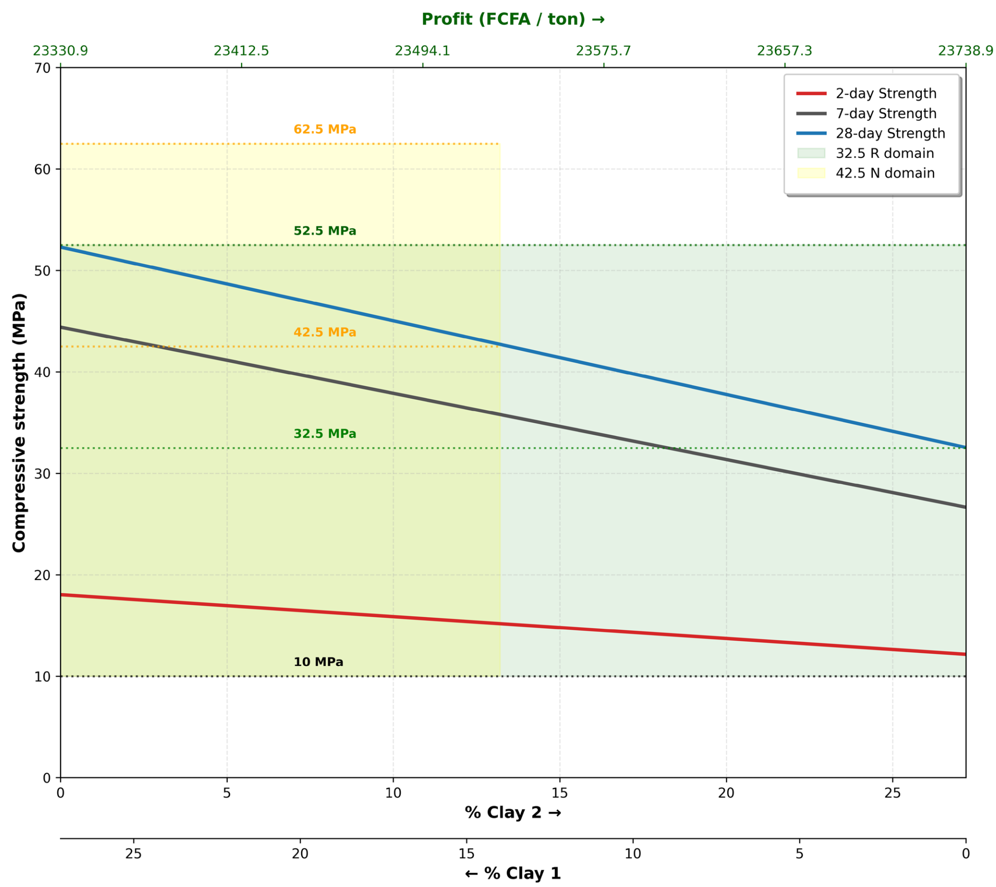

Figure 6. Changes in strength at 2 days, 7 days, and 28 days as a function of the percentages of Clay 1 and Clay 2 in the first series of mixtures.

obtain these two cement strength classes.

Class 42.5 N is met when the 2-day strength curve is above 10 MPa and the 28-day strength curve is between 42.5 MPa and 62.5 MPa. In contrast, Class 32.5 R is achieved when the 2-day strength curve is above 10 MPa and the 28-day strength curve is between 32.5 MPa and 52.5 MPa. These conditions are met if:

- 0 ≤ % Clay 2 ≤ 13.2 for the formulation of 42.5 N cement with 50% clinker, 20% limestone, 2.8% phosphogypsum, and a clay 1 content ranging from 14 to 27.2 (Figure 6). This corresponds to a profit margin ranging from 23330.9 to 23528.9 CFA francs per ton;
- 0 ≤ % Clay 2 ≤ 27.2 for the formulation of 32.5 R cement with 50% clinker, 20% limestone, 2.8% phosphogypsum, and a clay 1 content ranging from 0 to 27.2 (Figure 6), thereby covering a profit margin ranging from 23330.9 to 23738.9 CFA francs per ton;
- 0 ≤ % Clay 2 ≤ 6.7 for the formulation of 32.5 R cement with 40% clinker, 30% limestone, 2.8% phosphogypsum, and a clay 1 content ranging from 27.2 to 20.5% (Figure 7), ensuring a profit margin ranging from 29844.8 to 29945.3 CFA francs per ton.

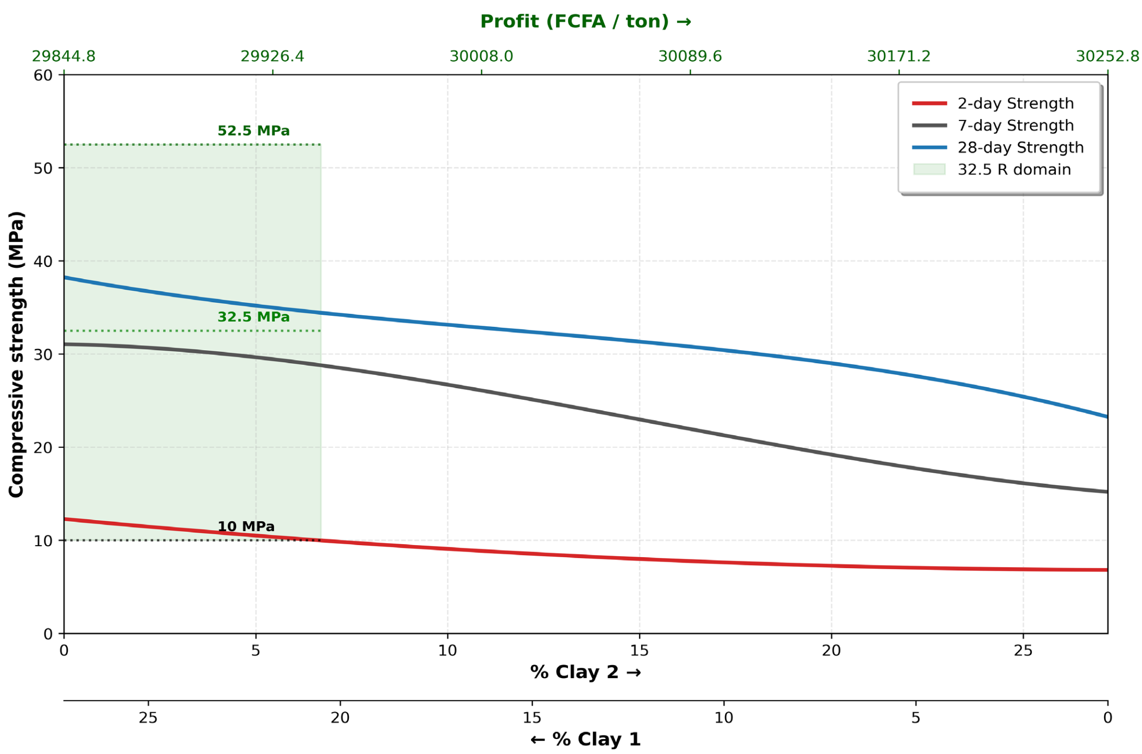

Figure 7. Changes in strength at 2 days, 7 days, and 28 days as a function of the percentages of Clay 1 and Clay 2 in the second series of mixtures.

4. Conclusion

This study demonstrated the technical feasibility of formulating LC3 binders using a binary clay blending strategy, combining a low-kaolinite clay (Clay 2, 2.6% kaolinite) with a highly reactive, kaolinite-rich clay (Clay 1, 70% kaolinite). By varying their proportions across two series of mixtures containing 50% and 40% clinker, the experimental results highlighted the synergy between the two precursors: while Clay 1 provides the necessary pozzolanic reactivity after calcination into metakaolin, its combination with Clay 2 allows efficient clinker substitution while maintaining performance. Mathematical modeling using mixture plans provided reliable predictive equations, enabling the identification of formulation ranges compatible with cement classes 32.5 R and 42.5 N. These results confirm the technical feasibility of producing LC3 cements that comply with current standards, including those with a clinker content reduced to 40% for the 32.5 R grade, thereby opening up promising prospects for reducing the cement industry's carbon footprint. Further investigations, focusing in particular on durability, workability, and life cycle analysis, would help consolidate these results with a view to industrial application.

Author Contributions

- **Conceptualization:** Mame Arame Ousmane NDIAYE, Mamadou Moustapha DIOUF, and Alpha Ousmane TOURE
- **Methodology:** Mamadou Moustapha DIOUF, Mame Arame Ousmane NDIAYE, and Alpha Ousmane TOURE
- **Software and Mathematical Modelling**: Mamadou Moustapha DIOUF and Mame Arame Ousmane NDIAYE
- **Validation:** Mouhamadou Bachir LO, Mamadou FAYE, Mamadou GOME, Mamadou SENGHOR, and Farba Bouyagui TAMBOURA
- **Formal Analysis:** Mamadou Moustapha DIOUF, Mame Arame Ousmane NDIAYE, and Alpha Ousmane TOURE
- **Investigation and Experimental Work:** Mame Arame Ousmane NDIAYE, Mamadou Moustapha DIOUF, Mamadou GOME, and Mamadou SENGHOR
- **Resources:** Mouhamadou Bachir LO, Mamadou GOME, Mamadou SENGHOR, and Farba bouyagui TAMBOURA
- **Data Curation:** Mamadou Moustapha DIOUF and Mame Arame Ousmane NDIAYE
- **Writing Original Draft Preparation**: Mamadou Moustapha DIOUF and Mame Arame Ousmane NDIAYE
- **Writing Review & Editing:** Mame Arame Ousmane NDIAYE, Mamadou Moustapha DIOUF, Alpha Ousmane TOURE
- **Visualization:** Mamadou Moustapha DIOUF and Mame Arame Ousmane NDIAYE
- **Supervision:** Alpha Ousmane TOURE, Mamadou FAYE, and Farba Bouyagui TAMBOURA

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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