Civil Engineering Dimension
https://ced.petra.ac.id

# Fresh and Mechanical Properties of Limestone Calcined Clay Cement (LC3) using Local Clay with Clinker Content below 50%

**Mihardja, E.**[1], **Antoni**[1]*, **Riady, E.G.**[1], **Suhendro, S.V.**[1], **Susanto, T.E.**[2], **Akbar, R.T.**[2], **Anuraga, B.T.T**[2], **and Hardjito, D.**[1]
[1] Civil Engineering Department, Faculty of Civil Engineering and Planning, Petra Christian University
Jl. Siwalankerto 121-131, Surabaya 60236, INDONESIA
[2] Research and Development Division, Semen Indonesia, Jl. Veteran, Gresik, 61122, INDONESIA

DOI: https://doi.org/10.9744/ced.28.1.120-129

***Article Info:***
Submitted: June 15, 2025
Reviewed: Oct 22, 2025
Accepted: Jan 13, 2026

***Keywords***:
Limestone Calcined Clay Cement (LC3),
Low Carbon Cement (LCC),
local clay,
low clinker,
compressive strength.

***Corresponding Author:***
**Antoni**
Civil Engineering Department,
Faculty of Civil Engineering and Planning,
Petra Christian University
Jl. Siwalankerto 121-131, Surabaya
60236, INDONESIA
Email: antoni@petra.ac.id

## Abstract

This study examined the performance of limestone calcined clay cement (LC3) produced with Indonesian clays containing low–medium kaolinite (20–30%) and clinker contents below 50%. Material characterization was carried out using XRF, XRD, and particle size analysis, followed by evaluation of fresh and mechanical properties. LC3 mixtures incorporating local clays exhibited good workability and required less superplasticizer than metakaolin-based controls, indicating favourable fresh behaviour despite reduced clinker content. A notable strength reduction was observed when clinker content dropped below 35%, reflecting insufficient portlandite required for pozzolanic reactions. The addition or substitution of $Ca(OH)_2$ did not improve strength and hindered calcined clay reactivity due to elevated pH level (12.5–13.5). Microstructural analysis confirmed that mixtures with higher kaolinite and clinker contents produced denser hydration products. The results demonstrated that Indonesian clays are suitable for LC3 development, with promising fresh properties and microstructural behaviour supporting further optimization and future durability studies.

## INTRODUCTION

Limestone calcined clay cement (LC3) is a breakthrough in the construction industry because of its lower carbon footprint. LC3 composition comprises 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. LC3 decreases $CO_2$ emissions by lowering the clinker ratio in the production of ordinary Portland cement (OPC). The availability of local clay and their thermal activation at 600-850°C yield energy savings by enabling lower calcination temperatures compared to clinkering. The LC3 approach for $CO_2$ reduction decreases direct emissions by 35% relative to OPC in the cement industry [1-3]. Hence, it makes clay suitable as an alternative to the available supplementary cementitious material (SCM) e.g. fly ash, blast furnace slag, silica fume [4,5]

The pozzolanic reaction of calcined clay with portlandite during hydration, the reaction of portlandite and tricalcium aluminate ($C_3A$) with limestone to form monocarboaluminate (Mc) and hemicarboaluminate (Hc) [6,7], and the reaction of aluminate from calcined clay with limestone to form additional Mc and Hc are the main factors which are providing LC3 mechanical and durability properties similar to OPC. Additionally, filler effect of limestone with

**Note** : Discussion is expected before July, 1st 2026, and will be published in the “Civil Engineering Dimension”, volume 28, number 2, September 2026.
**ISSN** : 1410-9530 print / 1979-570X online
**Published by** : **Petra Christian University**

Blaine fineness of 510–520 $m^2$/kg and mean size particle diameter (d50) of 2–10 µm observed by Tironi et al. [8] and Shao et al. [9] will result in a denser microstructure.

Ruan et al. [10] and Zhang et al. [11] examined the feasibility of higher clinker replacement and the microstructure and compressive strength of LC3 with clinker replacement ranging from 50 to 80% by weight. It was found that 70% by weight may represent the highest substitution level. The limited presence of portlandite produced during clinker hydration could restrict the pozzolanic reaction of calcined clay. Zunino et al. [12] and Sun et al. [13] noted that LC3-35, formulated with clay including 63% by weight kaolinite and a 2:1 ratio of calcined clay to limestone, had significantly greater compressive strength than the commercially available general use pozzolanic cement with a clinker content of 65% by weight. However, the calcined clay utilized in the above studies comprises a high kaolinite content, ranging from 40% to 60% by weight, which may not be accessible in other regions. Particularly the clay in Indonesia, which possesses a lower kaolinite content relative to other global regions [14]. Clay and limestone are abundantly available in Indonesia which could meet large-scale cement production demand. Furthermore, the cement consumption is predicted increasing in the future. There is high possibility for a significant substitution of calcined clay and limestone for cement.

The study aims to explore further the impact of the usage of local clay with low until medium kaolinite content with range between 20%–30% in East Java, Indonesia, with a reduced clinker content lower than 50% on fresh and mechanical properties of LC3 [15]. The variables used in this study are the local clay from three different regions in East Java, Indonesia and clinker content substitution. The specific gravity and particle sieve analysis (PSA) of each material was examined in the first stage. The local clay was analysed by X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) to determine the characteristic and kaolinite content. Fresh properties assessment was commenced by testing the paste material for its setting time and normal consistency. Workability and flowability characteristic of each mixture proportion design was assessed by flow table. The compressive strength examination of each mortar mix design was conducted at ages 7, 14, 28, and 56 days. The test results were then compared to the compressive strength of control specimen with metakaolin [16,17]. Scanning Electron Microscope (SEM) examination was conducted to evaluate the microstructure development by employing secondary electron (SE) and backscattered electron (BSE) method. Hence, the degree of hydration and matrix densification in the mortar can be examined to support the interpretation of mechanical performance. It is expected that the outcomes of the study contribute to evaluate the local clay usage in Indonesia for further development in LC3 production.

## MATERIAL PREPARATION

The study incorporated clays from different region in East Java, Indonesia to create an appropriate LC3 system. The clinker was obtained from Gresik plant, one of plant member of PT Semen Indonesia, while the clay was acquired from Trenggalek (A), Surabaya (B), and Madiun (C). The utilized fine aggregate was Lumajang sand, with a fineness modulus of 2.14 according to ASTM C778-21 [18]. Limestone powder, gypsum and kaolin were procured from local supplier. Seven kilograms of raw clay A, 4 kg each of raw clays B and C, and 4 kg kaolin were oven-dried for 24 hours, and then calcined at 750°C for 90 minutes in a laboratory furnace, as shown in Table 1. Upon completion of the calcination process, the kaolin and clays were allowed to cool for 2 hours and were then stored in airtight container. The calcined clays were subsequently pulverized using a ball mill. The particle size distribution of each calcined clay is shown in Figure 1.

**Table 1.** Clay and Kaolin Treatment, in Calcined and Milled Form

| | Before treatment | Calcined at 750°C | Milled |
|---|---|---|---|
| Clay A, Trenggalek |  |  |  |
| Clay B, Surabaya |  |  |  |
| Clay C, Madiun |  |  |  |
| Kaolin |  |  | |

## MIXTURE PROPORTION DESIGN AND METHODOLOGY

The mixture proportion design of mortar specimen is displayed in Table 2. Source of clay and clinker content served as variable in this study. A water to binder mass ratio (w/b) of 1:2, a limestone to calcined clay ratio (LS/CC) of 1:2, and a binder to sand mass ratio (b/s) of 1:2 was applied in the mixture proportion. The gypsum percentage remained constant throughout all mixture proportions, which is maintained at 0.6% of the total binder weight.

The fresh properties of each mixture design were evaluated with the Vicat Apparatus to ascertain initial setting time, and flow table to determine the normal consistency according to ASTM C187-16 and ASTM C191-21 [19,20], respectively. The addition of superplasticizer (SP) was determined during the flow table test. It was added incrementally until the mixture achieved a flow diameter ranging between 15-17 cm using flow table test. Normal consistency denoted the ideal water quantity necessary for ensuring workability, whilst the initial setting time represented the reaction rate of the mixture. The impact of calcium hydroxide, $Ca(OH)_2$, introduction for strength development improvement at lower percentage of clinker-to-mass ratio at 30% by weight were examined [13]. As an addition (ADD), $Ca(OH)_2$ will replace part of the calcined clay. Replacement (SUB) allows $Ca(OH)_2$ to replace part of the limestone without changing the calcined clay.

**Table 2**. Mixture Proportion Design of Mortar Specimen

| Mixture | Binder | | | | | | Sand (gr) | Water (gr) |
|---|---|---|---|---|---|---|---|---|
| | Clinker (gr) | Calcined clay (gr) | Kaolin (gr) | Limestone (gr) | Gypsum (gr) | $Ca(OH)_2$ (gr) | | |
| MK50 | 250 | - | 164.7 | 82.3 | 3 | - | 1000 | 250 |
| MK45 | 225 | - | 181.3 | 90.7 | 3 | - | 1000 | 250 |
| A45 | 225 | 181.3 | - | 90.7 | 3 | - | 1000 | 250 |
| B45 | 225 | 181.3 | - | 90.7 | 3 | - | 1000 | 250 |
| C45 | 225 | 181.3 | - | 90.7 | 3 | - | 1000 | 250 |
| MK40 | 200 | - | 198.0 | 99.0 | 3 | - | 1000 | 250 |
| A40 | 200 | 198.0 | - | 99.0 | 3 | - | 1000 | 250 |
| B40 | 200 | 198.0 | - | 99.0 | 3 | - | 1000 | 250 |
| C40 | 200 | 198.0 | - | 99.0 | 3 | - | 1000 | 250 |
| MK30 | 150 | - | 231.3 | 115.7 | 3 | - | 1000 | 250 |
| A35 | 175 | 214.7 | - | 107.4 | 3 | - | 1000 | 250 |
| A30 | 150 | 231.3 | - | 115.7 | 3 | - | 1000 | 250 |
| A30 CH1:1 ADD | 150 | 173.5 | - | 86.8 | - | 86.8 | 1000 | 250 |
| A30 CH2:1 ADD | 150 | 198.3 | - | 99.1 | - | 49.6 | 1000 | 250 |
| A30 CH1:1 SUB | 150 | 231.3 | - | 57.8 | - | 57.8 | 1000 | 250 |
| A30 CH2:1 SUB | 150 | 231.3 | - | 77.1 | - | 38.6 | 1000 | 250 |

The compressive strength of the mortar was assessed using 50 mm cubes as per ASTM C109M-20 [21]. Specimens were immersed in water for curing and were extracted only one day prior to the scheduled testing. Compressive strength testing was performed on samples at 3, 7, 28 and 56 days.

## RESULTS AND DISCUSSION

### Material Characterization

Table 3 displays the estimated percentage of kaolinite by weight in the calcined clay which is calculated by accounting for mass loss between 400°C and 650°C, while considering the respective atomic masses of kaolinite, $Al_2(OH)_4Si_2O_5$ and water, $H_2O$. The estimated kaolinite content in calcined clays was calculated using Equation 1.

$$wt\%\ kaolinite = wt\%\ loss \cdot \frac{Mkaolinite}{2M\ water} \tag{1}$$

Where: $wt\%_{kaolinite}$ = Kaolinite content in calcined clay
$wt\%_{loss}$ = Mass loss between 400°C–650°C
$M_{kaolinite}$ = Atomic mass of kaolinite
$M_{water}$ = Atomic mass of water

**Table 3.** Estimated Kaolinite Content in Percentage by Weight and Specific Gravity

| Material | wt% $_{\text{loss}}$ | wt% $_{\text{kaolinite}}$ | Specific Gravity |
|---|---|---|---|
| Metakaolin | 8.90 | 66.9 | 2.40 |
| Calcined clay A | 7.05 | 55.3 | 2.48 |
| Calcined clay B | 7.69 | 51.0 | 2.52 |
| Calcined clay C | 3.61 | 26.3 | 2.56 |
| Gypsum | N.A. | N.A. | 2.70 |
| Limestone | N.A. | N.A. | 2.73 |
| Clinker | N.A. | N.A. | 3.00 |

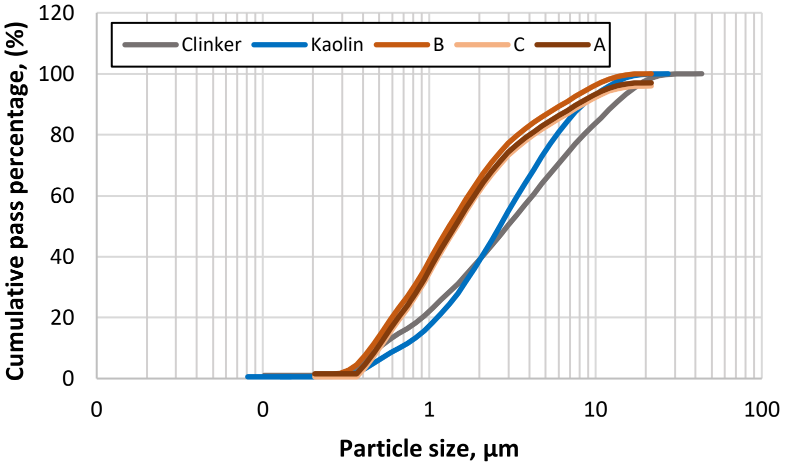


**Figure 1.** Particle Size Distribution of Calcined Clay A (Trenggalek), B (Surabaya), C (Madiun), Metakaolin and Clinker

The specific gravity was determined according to ASTM C188-17 [22] with kerosene as medium. Clinker possesses the highest specific gravity with 3.00 as shown in Table 3. Limestone and gypsum exhibit nearly identical specific gravities with 2.70 and 2.73, while metakaolin shows the lowest specific gravity among three types of calcined clay with 2.40. The particle size distribution of each material is displayed in Figure 1. Material with finer particle size, such as metakaolin (~2 µm) and calcined clay A, B and C (~3-4 µm), generally exhibit lower specific gravity (2.48–2.56) compared with clinker, which has a coarser particle size (~5 µm) and a higher specific gravity of approximately 3.00. Finer particle size from metakaolin and calcined clay are increasing the specific surface area. Hence, expediting the pozzolanic reaction despite their lower specific gravity. It can be inferred also from Table 3 and XRD test results in Table 5 that calcined clay A with the highest kaolinite content hold the lowest specific gravity with 2.48 compared to the other clay with a lower kaolinite content. XRF test results as displayed in Table 3 indicate that the sum of silicon dioxide ($SiO_2$), aluminium oxide ($Al_2O_3$) and ferric oxide ($Fe_2O_3$) from clay is more than 70% which plays a significant role in pozzolanic reaction. Based on XRF and PSA result, the clay satisfies the chemical and physical requirement of ASTM C618-19 [23]. However, the loss on ignition (LOI) will be reduced by calcination to meet the pozzolanic material requirement.

**Table 3.** Chemical Composition of Three Clay Types and Kaolin Determined by XRF prior to Calcination

| Composition | Chemical formula | Result (in wt%) | | | |
|---|---|---|---|---|---|
| | | Kaolin | Clay A | Clay B | Clay C |
| Silicon dioxide | $SiO_2$ | 49.72 | 51.31 | 55.51 | 51.42 |
| Aluminium oxide | $Al_2O_3$ | 31.99 | 21.14 | 18.14 | 22.16 |
| Ferric oxide | $Fe_2O_3$ | 0.87 | 7.94 | 6.90 | 6.65 |
| Calcium oxide | CaO | 0.22 | 1.11 | 1.11 | 3.56 |
| Magnesium oxide | MgO | 0.20 | 1.58 | 1.79 | 0.99 |
| Sulphur trioxide | $SO_3$ | <0.001 | 0.02 | 0.16 | 0.19 |
| Sodium oxide | $Na_2O$ | 1.11 | 0.82 | 0.62 | 1.87 |
| Potassium oxide | $K_2O$ | 0.09 | 0.87 | 1.29 | 0.85 |
| Phosphorus pentoxide | $P_2O_5$ | <0.001 | 0.12 | 0.09 | 0.19 |
| Titanium oxide | $TiO_2$ | 0.12 | 1.01 | 1.25 | 0.99 |
| Loss on ignition (LOI) | | 14.26 | 13.73 | 12.68 | 10.73 |

XRD test results in Table 5 and Figure 2 showed that these clays have varying composition in their crystal form. The primary crystal composition of these clays consists of quartz, kaolinite, montmorillonite and illite. Clay A and C are predominantly composed of kaolinite with 29.73% and 14.48% by mass respectively, whereas clay B is primarily composed of illite with 18.90% by mass, which is less reactive material and have a less pozzolanic reactivity compared to clay A and C.

**Table 5.** Mineralogy Composition of Three Clay Types Determined by XRD prior to Calcination

| Mineralogy Composition | Chemical Formula | Result (in wt%) | | | |
|---|---|---|---|---|---|
| | | Kaolin | Clay A | Clay B | Clay C |
| Andesine | $(Rb_{0.811}Al_{0.062})(Al_{0.997}Si_{3.003}O_8)$ | - | 5.29 | 2.26 | 28.42 |
| Quartz | $SiO_2$ | 0.40 | 15.18 | 34.41 | 0.07 |
| Montmorillonite | $Ca_{0.5}(Al_2Si_4O_{11}(OH))$ | - | 3.37 | 0.98 | 3.64 |
| Sanidine | $Na_{0.1}K_{0.83}AlSi_3O_8$ | - | 4.56 | 0.88 | 2.28 |
| Nontronite | $Na_{0.3}Fe_2((Si,Al)_4O_{10})(OH)_2 \cdot nH2O$ | - | 4.89 | 2.74 | 3.31 |
| Kaolinite | $Al_4(OH)_8(Si_4O_{10})$ | 96.80 | 29.73 | 16.00 | 14.48 |
| Cristobalite | $SiO_2$ | | 2.23 | 1.34 | 5.01 |
| Illite | $Al_4KO_{12}Si_2$ | 0.50 | 2.50 | 18.90 | 0.96 |
| Vermiculite | $Mg_3(Si_4O_{10})(OH)_2$ | - | 4.41 | 7.02 | 3.38 |
| Nacrite | $Al_2Si_2O_5(OH)_4$ | - | 4.47 | 8.14 | 2.43 |
| Gypsum | $CaSO_4\ 2(OH)_4$ | - | 0.56 | 0.30 | 0.40 |
| Other | | - | 22.81 | 7.03 | 35.62 |

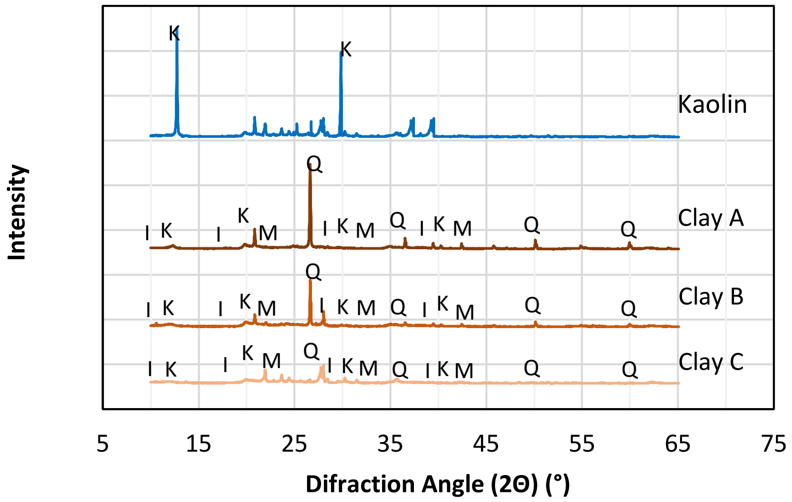


**Figure 2.** XRD Patterns of Kaolinite (K), Illite (I), Montmorillonite (M) and Quartz (Q) in Raw Clays A (Trenggalek), B (Surabaya), and C (Madiun), and in Kaolin before Calcination

## Fresh Properties

### Normal Consistency

The test result for normal consistency and initial setting time which were performed on the mixture paste, is displayed in the Figure 3. It can be observed that there is a direct correlation between kaolinite content and water demand. As kaolinite content increased, a water demand is expected correspondingly to be increased. LC3 containing local clay exhibited lower figures in water demand than the control specimen with metakaolin. It can be observed in this study that the workability of LC3 is higher than the control specimen with metakaolin. Clay C has shown the best workability among all clays as the water demand is lower than the other clay. The same result is shown for the LC3 with both additional and substitution of portlandite. Based on the findings above, it can be inferred that an increase in metakaolin content resulted in diminished workability. The water demand at normal consistency values was observed to align with the calculated kaolinite content in each clay sample, where the control specimen with metakaolin necessitating the greatest water-to-binder ratio.

It was found that mixture proportion exhibited an elevated normal consistency will require a prolonged duration to attain their initial setting time. As the limestone content in the LC3 specimen is increased, the initial setting time will reach faster compared to the control specimen with metakaolin. It is possibly attributable to the limestone capacity for water absorption, which accelerated the setting process. This can be observed in SEM image in Figures 7 and 8, which displayed compact microstructure. Discrepancies in the consistency and setting time of the LC3 mixture proportion were noted to changes in clay type, particularly the kaolin content in each clay.

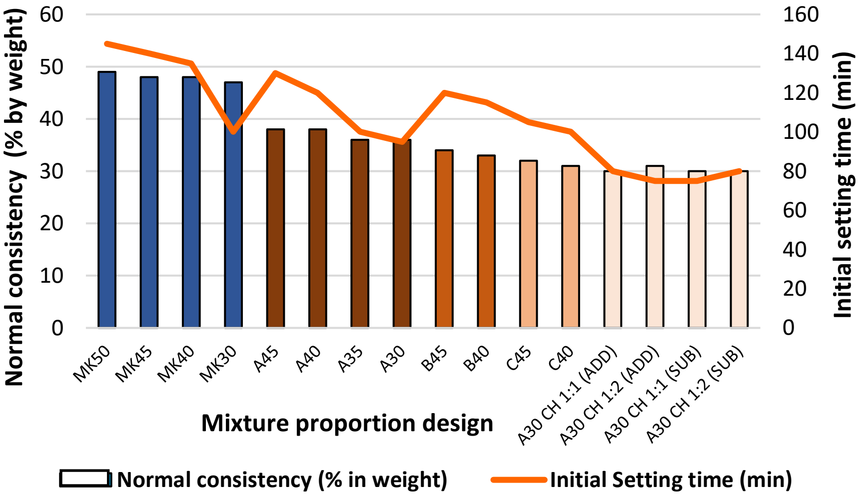


**Figure 3.** Correlation between Normal Consistency and Initial Setting Time

## Flow Table

Figure 4 illustrates the superplasticizer (SP) dosage, which is showing the percentage of SP quantity relative to the binder mass. Metakaolin required a higher quantity of SP than other calcined clay. This results from metakaolin's lower specific gravity relative to other clays, leading to a greater casting volume for metakaolin than for other calcined clays of same total mass. Furthermore, another tendency indicates that as clinker content diminishes, the required quantity of SP also declines.

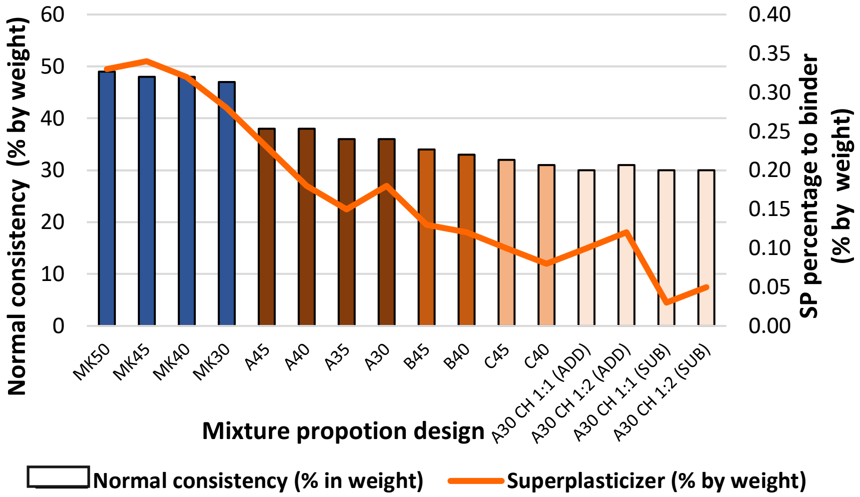


**Figure 4.** Correlation between Normal Consistency and Addition of Superplasticizer

## Compressive Strength Development

The compressive strength tests for all specimens at 7, 14, 28 and 56 days are shown in Figure. 5. Both control (MK50, MK45, MK40, MK30) and LC3 specimen (A45, A40, A35, A30, B45, B40, C45 and C40) exhibited encouraging initial strengths at 7 and 14 days. MK45 at 56 days demonstrated a compressive strength that is 7% higher than that of C45, while compressive strength of MK45 at early age is 14% higher than C45. The similar trend is also observed in the MK40 compared to C40, indicating that higher kaolinite concentration is a contributing factor to strength development at early age.

LC3 displayed a further strength development compared to the control specimen with metakaolin at later age. The control specimen with metakaolin demonstrated a relatively stable in strength development after 28 days [24]. Despite clay C has the lowest kaolinite content among all clay types, the compressive strength of the LC3 with clay C was comparable to control specimen with metakaolin with 40% clinker content. LC3 with clay A and B attained comparable compressive strength especially at 56 days with control specimen with metakaolin.

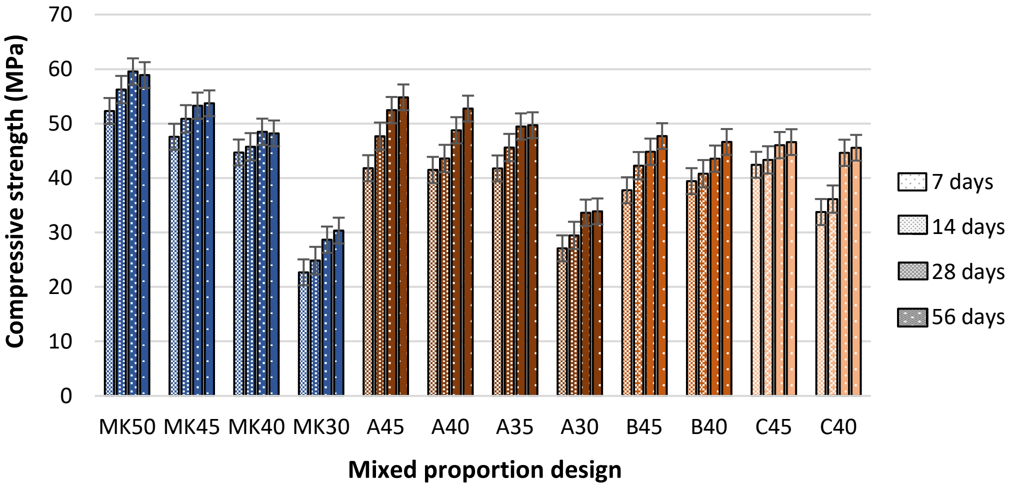


**Figure 5.** Compressive Strength Development of Each Mixture Proportion Design

The compressive strength showed a tendency to decrease with the decreasing percentage of clinker in the mixture proportion design. The decrease in compressive strength is attributed not only to the lower clinker content. It also corresponds to the kaolinite content in clay. While kaolinite promotes pozzolanic reaction by producing additional calcium alumina silicate hydrate gel (C-A-S-H), it may not be sufficient to compensate the shortcoming of calcium silicate hydrate gel (C-S-H) at lower clinker content. This situation can be explained as the clinker content lessens, the availability of $Ca(OH)_2$ also reduces, limiting metakaolin pozzolanic reactivity with $Ca(OH)_2$ to form C-A-S-H. Hence, as fewer hydration products are produced and lead to a decrease in a reduction in compressive strength. It cannot entirely prevent the performance reduction resulting from a significant reduction in clinker unless compensated by clay with higher kaolinite content or additional activator.

A remarkable reduction in compressive strength was exhibited in A30. This phenomenon aligns with prior studies from Zunino et al. [25] and indicating that a reduction in clinker content diminishes the quantity of $Ca(OH)_2$ in the system, resulting in kaolinite serving solely as a filler. The effect of the addition and substitution of limestone $Ca(OH)_2$ to LC3 mixture with clinker content at 30% by weight on the compressive strength was explored in this study. As illustrated in Figure 6, both addition and substitution of $Ca(OH)_2$ reduced the compressive strength compared with A30. It is contrary to the expectation that the hydration reaction will be improved by generating more C-A-S-H and contributing to the strength development. However, it can be also noticed that LC3 with additional $Ca(OH)_2$ consistently demonstrated higher compressive strength at all ages compared to the specimen with substitution of limestone with $Ca(OH)_2$.

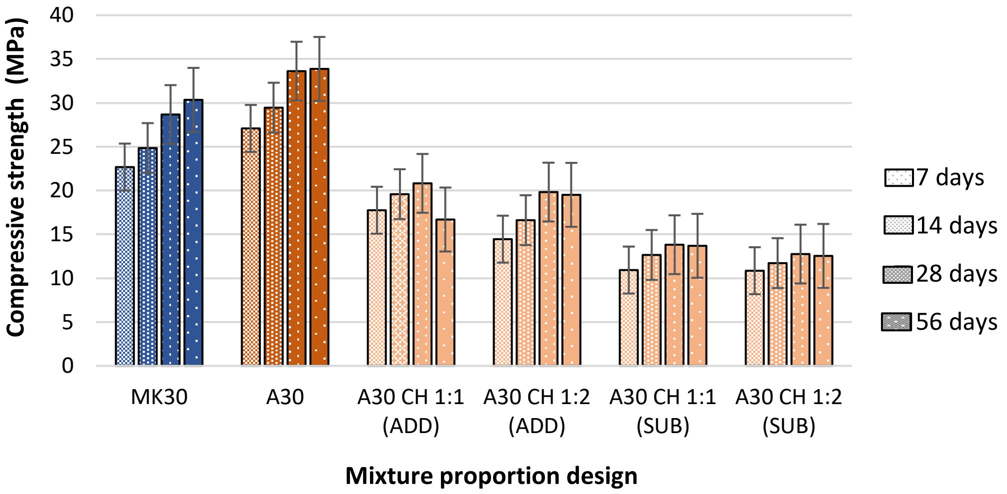
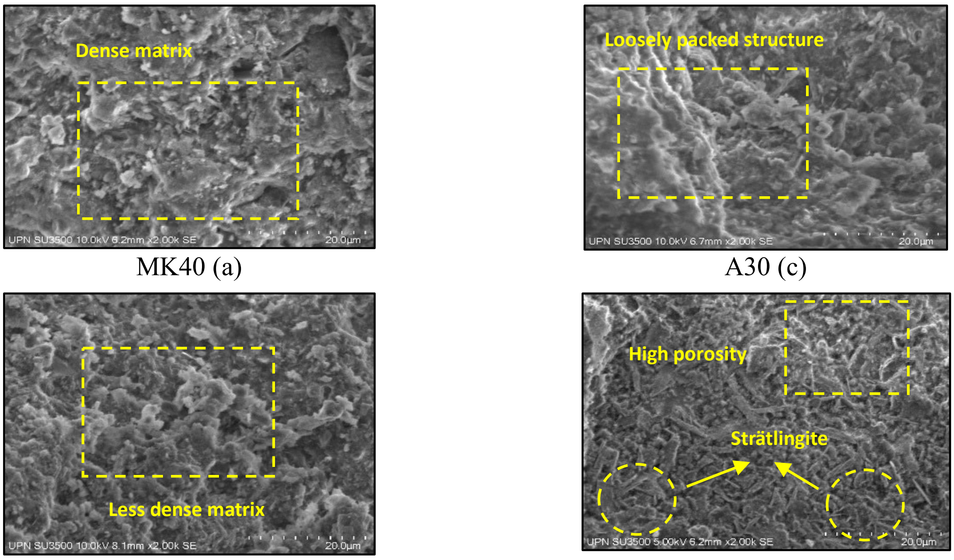


**Figure 6.** Compressive Strength Development of Each Mixture Proportion Design with $Ca(OH)_2$

The additional $Ca(OH)_2$ will add solely portlandite instead of producing C-S-H and C-A-S-H. It doesn't significantly enhance the strength development as the kaolinite content in calcined clay itself is adequate in promoting pozzolanic reaction to form additional C-A-S-H. Substituting limestone with $Ca(OH)_2$ disrupts the filler effect provided by limestone, which is responsible for denser microstructure [26,27]. The increased pH from 12 to 13 from $Ca(OH)_2$ will furthermore reduce the reactivity of calcined clay. Hence, the pozzolanic reaction will be limited. There are two opposing effects in pH increase, it will enhance the metakaolin dissolution and inhibiting the portlandite dissolution. As there is high dissolution of metakaolin, it has the possibility also to promote the formation of strätlingite ($C_2ASH_8$) and ettringite which is less effective in strength development [28,29]. With a lower clinker content at 30%, the system relies heavily on pozzolanic reactions, which are negatively affected by the presence of $Ca(OH)_2$.

## Microstructure Analysis

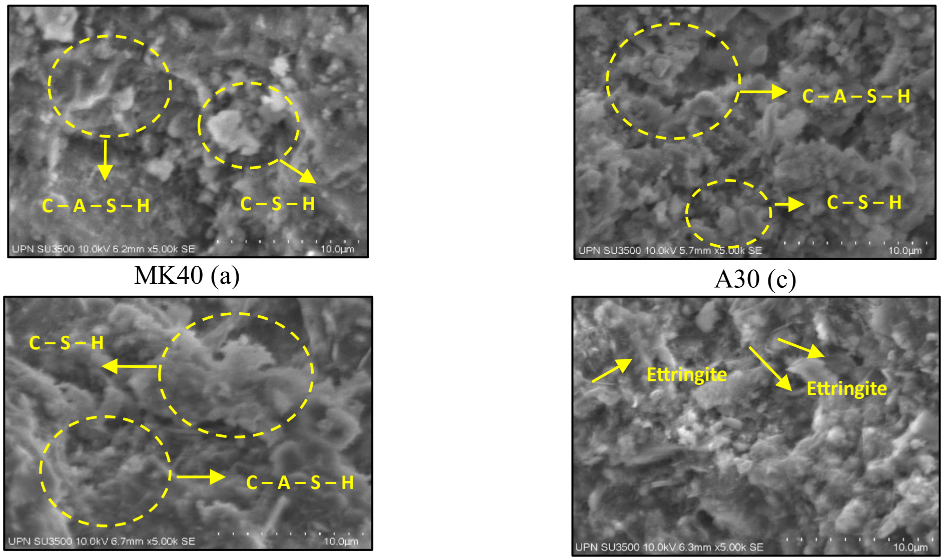
The SEM image of metakaolin (MK40) and LC3 (A40, A30 and A30 with additional $Ca(OH)_2$) in Figures 7 and 8 showed a pronounced contrast in microstructural density and hydration product morphology. As shown in Figures 7(a) and 8(a), MK40 in displayed the most compact and dense matrix, correlating with well-developed C-A-S-H gel formation due to metakaolin high pozzolanic reactivity. A40 in Figures 7(b) and 8(b) exhibited a relatively dense microstructure compared to the control specimen MK40. On the other hand, A30 in Figures 7(c) and 8(c) had a more porous and loosely packed structure compared with A40 in Figures 7(b) and 8(b), with more visible void and unreacted particles, indicating a lower pozzolanic activity.



MK40 (a) A30 (c)

A40 (b) A30 CH 1:1 (ADD (d)

**Figure 7.** SEM Images of Metakaolin (MK40) and LC3 Mixtures (A40, A30, A30 with Additional $Ca(OH)_2$) at 2000x Magnification



MK40 (a) A30 (c)

A40 (b) A30 CH 1:1 (ADD) (d)

**Figure 8.** SEM Images of Metakaolin (MK40) and LC3 Mixtures (A40, A30, A30 with Additional $Ca(OH)_2$) at 5000x Magnification

In comparison with A30, A30 CH 1:1 (ADD) showed a highly porous matrix with flake and needle-like crystalline structures, most probably identified as strätlingite ($C_2ASH_8$) and ettringite, are displayed in Figures 7(d) and 8(d) [30], suggesting that the addition of $Ca(OH)_2$ did not enhance pozzolanic activity. These findings correspond with the mechanical performance trends, validating that kaolinite and clinker content are the main contributor to the density and strength development of the LC3 matrix.

## CONCLUSIONS

1. LC3 with local clays usage demonstrated better workability and lower superplasticizer demand even with clinker content less than 50%.
2. The compressive strength of LC3 with clinker content less than 35% showed however a remarkable decrease. The same trend was also displayed on the metakaolin as control specimen.
3. The addition or substitution of $Ca(OH)_2$ in LC3 with 30% clinker content unexpectedly exhibited a reduction in compressive strength at all ages, despite the anticipated improvement in hydration and C-A-S-H formation.
4. Pozzolanic reaction will be limited by increasing pH from 12.5 to 13.5 resulted from additional $Ca(OH)_2$. A pH range between 11 and 12.5 is preferable to optimize the pozzolanic reactivity in LC3 mixture. It is recommended to have a Fourier Transformation Infrared Spectroscopy (FTIR) analysis in the future study to explore the pozzolanic reaction and its hydration product.
5. As LC3 with even with low clinker showing promising development in microstructure, it is recommended also to have a durability test in both laboratory scale and actual field in certain period of time, especially in marine environment. Long term permeability or diffusivity test and SEM are recommended also to verify the durability and microstructure development.

## ACKNOWLEDGEMENT

This work was supported by the Government of the Republic of Indonesia through the Ministry of Higher Education, Science, and Technology. The authors also acknowledge PT Semen Indonesia for providing materials and technical support that facilitated this study. The sponsors had no role in the study design, data analysis, or interpretation of results.

## REFERENCES

1. Al-Fakih, A., Al-Shugaa, Al-Osta, M.A., and Thomas, B.S., Mechanical, Environmental, and Economic Performance of Engineered Cementitious Composite Incorporated Limestone Calcined Clay Cement: A review, *Journal of Building Engineering*, 79, 2023, pp 1-18, doi: 10.1016/j.jobe.2023.107901.
2. Barbhuiya, S, Nepal, J., and Das, B.B., Properties, Compatibility, Environmental Benefits and Future Directions of Limestone Calcined Clay Cement (LC3) Concrete: A Review, *Journal of Building Engineering*, 79, 2023, pp 1-26, doi: 10.1016/j.jobe.2023.107794.
3. Scrivener, K., Martirena, F., Bishnoi, S., and Maity, S., Calcined Clay Limestone Cements (LC3), *Cement and Concrete Research*, 114, 2018, pp. 49–56, doi: 10.1016/j.cemconres.2017.08.017.
4. Wattimena, O.K., Antoni, A., and Hardjito, D., Long-term Mechanical Properties and Microstructure of Concrete Utilizing Self-Cementing Fly Ash as A Sole Binder Material, *Civil Engineering Dimension*, 25(2), 2023, pp. 106–114, doi: 10.9744/ced.25.2.106-114.
5. Sim, J. and Lee, K.H., Sustainable Concrete Technology, *Civil Engineering Dimension*, 17(3), 2015, pp. 158-165, doi: 10.9744/CED.
6. Overmann, S., Vollpracht, A., and Matschei, T., Reactivity of Calcined Clays as SCM-A Review, *Materials*, 17(2), 2024, pp. 1-24, doi: 10.3390/ma17020312.
7. Matschei, T., Lothenbach, B., and Glasser, F.P., The Role of Calcium Carbonate in Cement Hydration, *Cement and Concrete Research*, 37(4), 2007, pp. 551–558, doi: 10.1016/j.cemconres.2006.10.013.
8. Tironi, A., Scian, A.N., and Irassar, E.F., Blended Cements with Limestone Filler and Kaolinitic Calcined Clay: Filler and Pozzolanic Effects, *Journal of Materials in Civil Engineering*, 29(9), 2017, pp. 1-8, doi: 10.1061/(ASCE).
9. Shao, Z., Cao, M., and Zheng, X., Limestone Particle Sizes and Sulfate Impact on the Early Hydration of Limestone Calcined Clay Cement, *Journal of Building Engineering*, 97, 2024, pp. 1-20, doi: 10.1016/j.jobe.2024.110848.
10. Ruan, Y., Jamil, T., Hu, C., Gautam, B.P., and Yu, J., Microstructure and Mechanical Properties of Sustainable Cementitious Materials with Ultra-High Substitution level of Calcined Clay and Limestone Powder, *Construction and Building Materials*, 314, 2022, pp. 1-8, doi: 10.1016/j.conbuildmat.2021.125416.

11. Zhang, W., Sun, J., Zhang, N., Hou, G., Jiang, R., Li, W., and Yu, Z., Investigating the Potential of the Limestone Calcined Clay Cement with Cement Content Below 50 wt%: Hydration Properties and Environmental Impact Analysis, *Construction and Building Materials*, 411, 2024, pp. 1-15, doi: 10.1016/j.conbuildmat.2023.134264.
12. Zunino, F., Martirena Hernandez, J.F., and Scrivener, K., Limestone Calcined Clay Cements (LC3), *ACI Materials Journal*, 118(3), 2021, pp. 49-60, doi: 10.14359/51730422
13. Sun, J., Zunino, F., and Scrivener, K., Hydration and Phase Assemblage of Limestone Calcined Clay Cements (LC3) with Clinker Content Below 50%, *Cement and Concrete. Research*, 177, 2024, pp. 1-13, doi: 10.1016/j.cemconres.2023.107417.
14. Gingele, F.X., De Deckker, P., and Hillenbrand, C.D., Clay Mineral Distribution in Surface Sediments between Indonesia and NW Australia — Source and Transport by Ocean Currents, *Marine Geology*, 179(3), 2001, pp. 135-146, doi: https://doi.org/10.1016/S0025-3227(01)00194-3.
15. Antoni, A., Kuncoro, A., Fernaldy, I., Davian, M., Susanto, T.E., and Hardjito, D., Potential of Local Clay for the Development of Limestone Calcined Clay Cement in East Java, *The Proceedings of the 4th International Conference on Green Civil and Environmental. Engineering,* Denpasar, Indonesia, August 8-10, 2023, pp. 1-10, doi: 10.1051/e3sconf/202344501035.
16. Pillay, D.L., Olalusi, O.B., Kiliswa, M.W., Awoyera, P.O., Kolawole, J.T., and Babafemi, A.J., Engineering Performance of Metakaolin Based Concrete, *Cleaner Engineering and Technology*, 6, 2022, pp. 1-12, doi: 10.1016/j.clet.2021.100383.
17. Kumar, R., Singh, R., and Patel, M., Effect of Metakaolin on Mechanical Characteristics of the Mortar and Concrete: A Critical Review, *Materials Today: Proceedings*, 93, 2023, pp. 315–319, doi: 10.1016/j.matpr.2023.07.262.
18. ASTM C778-21, *Specification for Standard Sand*, ASTM International, 2021, doi: 10.1520/C0778-21.
19. ASTM C187-16, *Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste*, ASTM International, West Conshohocken, PA, 2023.
20. ASTM C191-21, *Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*, ASTM International, West Conshohocken, PA, 2021.
21. ASTM C109M-20*, Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] cube specimens)*, ASTM International, West Conshohocken, PA, 2020.
22. ASTM C118-17, *Test Method for Density of Hydraulic Cement*, ASTM International, West Conshohocken, PA, 2017.
23. ASTM C618-19, *Standard Specification for Coal Fly Ash and Raw and Calcined Natural Pozzolan for Use in Concrete*, ASTM International, West Conshohocken, PA, 2019.
24. Zunino, F. and Scrivener, K., Microstructural Developments of Limestone Calcined Clay Cement (LC3) Pastes after Long-term (3 years) Hydration, *Cement and Concrete Research*, 153, 2022, pp. 1-13, doi: 10.1016/j.cemconres.2021.106693.
25. Zunino, F. and Scrivener, K., Influence of Kaolinite Content, Limestone Particle Size and Mixture Design on Early-Age Properties of Limestone Calcined Clay Cements (LC3), *Proceedings of the 3rd International Conference on Calcined Clays for Sustainable Concrete*, New Delhi, India, October 15-17, 2019, pp. 331–337, doi: 10.1007/978-981-15-2806-4_39.
26. Boakye, K. and Khorami, M., Performance of Calcined Impure Kaolinitic Clay as a Partial Substitute for Portland Cement Concrete: A Review, *Journal of Composites Science*, 9(4), 2025, pp. 1-24, doi: 10.3390/jcs9040145.
27. Hernández-Carrillo, G., Durán-Herrera, A., and Tagnit-Hamou, A., Effect of Limestone and Quartz Fillers in UHPC with Calcined Clay, *Materials*, 15(21), 2022, pp. 1-19, doi: 10.3390/ma15217711.
28. Weise, K., Ukrainczyk, N., and Koenders, E., Pozzolanic Reactions of Metakaolin with Calcium Hydroxide: Review on Hydrate Phase Formations and Effect of Alkali Hydroxides, Carbonates and Sulfates, *Material and Design*, 231, 2023, pp. 1-23, doi: 10.1016/j.matdes.2023.112062.
29. Deng, G., He, Y., Lu, L., and Hu, S., The Effect of Activators on the Dissolution Characteristics and Occurrence State of Aluminum of Alkali-Activated Metakaolin, *Construction and. Building Materials*, 235, 2020, pp. 1-7, doi: 10.1016/j.conbuildmat.2019.117451.
30. Santacruz, I., De La Torre, A., Alvarez-Pinazo, G., Cabeza, A., Cuesta, A., Sanz, J., and Aranda, M.A.G., Structure of Stratlingite and Effect of Hydration Methodology on Microstructure, *Advances in Cement Research*, 28(1), 2015, pp. 13–22, doi: 10.1680/adcr.14.00104.