INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 9 (2024) 53-66
https://publisher.uthm.edu.my/ojs/index.php/ijie

Performance of Carbide Lime Waste Mortar via 24 Hours Accelerated CO_2 Curing

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DOI: https://doi.org/10.30880/ijie.2024.16.09.004

Article Info

Received: 16 April 2024
Accepted: 27 September 2024
Available online: 4 December 2024

Keywords

Accelerated CO_2 curing, carbide lime waste, CO_2 capturing, $CaCO_3$ precipitation, CO_2 sequestration, CO_2 storing

Abstract

This paper explores the use of Calcium Lime Waste (CLW) as a cementitious material for early CO_2 capture. CLW, primarily composed of Calcium Hydroxide $Ca(OH)_2$, has high CaO content, making it ideal for CO_2 sequestration. CLW was added to Ordinary Portland Cement (OPC) mortar as a 0-40% replacement, and fresh and hardened properties – including workability, density, compressive strength, and CO_2 capture – were analysed. The results indicated that 30% CLW replacement gave optimal performance, with high CO_2 capture at targeted compressive strength for load and non-load bearing applications. This mix also achieved the greatest $CaCO_3$ precipitation at 34.61% and maintained desired strength over time. Mercury Intrusion Porosimetry (MIP) analysis revealed a micro-filling effect, reducing pore size compared to the control. The study supports the potential of CLW as a sustainable CO_2 absorbent, promoting environmental sustainability through waste reuse and CO_2 sequestration in construction materials.

1. Introduction

In recent years, rapid construction and industrial development have generated large amount of wastes, creating significant environmental challenges. The increasing global demand for energy, especially from fossil fuels, has led to greater CO_2 emissions, contributing heavily to global warming [1], [2]. The cement industry, responsible for over 10% of global CO_2 emissions [3], is a significant contributor. By 2030, cement production is projected to exceed 5 billion tonnes, with an expected increase in CO_2 emissions. By 2040, the cement industry in Europe alone is projected to add 0.1% in annual CO_2 emissions [4], with countries like Iraq producing up to 16.6 million tonnes of Portland cement (PC) each year [5]. By 2050, the manufacturing of cement is anticipated to contribute around 5% of global CO_2 emissions, reaching 4390 Mt [6], [7]. This series of anticipated increments in carbon footprint has intensified the demand for sustainable materials and more effective waste management. Systematic approaches are essential for the sustainable growth of the concrete sector. A promising solution is the use of carbonation curing treatments [8], particularly accelerated carbonation treatment to expedite the process and enhance the material's capacity to sequester and capture carbon [9], [10]. This process, also known as "mineral CO_2 sequestration", converts CO_2 into carbonate minerals [11]. Materials containing a certain quantity of calcium-bearing phases can promote CO_2 sequestration and the formation of carbonate compounds [3]. Materials with high calcium content, such as steel slag and cement kiln dust, are particularly effective at capturing CO_2 [11], [12].

As an eco-friendly cementitious material, lime-based products have long been used to capture atmospheric CO_2, although the process is typically slow [13], [14]. Moreover, this slow carbonation process leads to low early age strength, which impacts their properties over time [15]. The rate of carbonation varies depending on the lime type, surface area, and particle size [15]. Some are highly reactive (such as $CaO/Ca(OH)_2$) and readily reacts with CO_2 while others have lower reactivity and requires some modifications in curing method to enhance the carbonation. In general, carbonation is a time-consuming process, and traditional curing methods for cement-based materials often result in porous microstructures. At a typical atmospheric CO_2 concentration of 4%, the carbonation reactions of cement-based materials occur slowly. To achieve higher carbonation rates, higher CO_2 concentrations and a controlled atmosphere have to be cultivated with the right temperature and relative humidity (RH). However, the relationship between early-age strength and CO_2 uptake varies among different concrete mixes, depending on factors such as mix type, cement/aggregate ratio, and curing conditions, including temperature, procedure, and pressure [16]. Thus, an accelerating CO_2 curing is crucial to improve the rate of CO_2 capture in construction materials.

Calcium carbide waste (CLW), also known as carbide lime or lime sludge, is a compelling solution. CLW is a byproduct of acetylene production [17]. With a high pH (pH > 12), CLW can leach harmful compounds and alkalis into the groundwater if left untreated [18]. Nevertheless, due to limited commercial uses for carbide lime, most producers are unwilling to pay the treatment and disposal costs associated with neutralising high pH, resulting in millions tonnes of carbide lime being collected as waste in lagoons, pits, and heaps around the world [19]. Carbide lime is the third heaviest by-product waste material in the world. The calcium carbide industry statistics showed that 1370 million tonnes of calcium carbide are produced globally every year [20], [21]. The equation from the acetylene gas production is as shown in Equation 1.

$$\begin{array}{cccccccc} CaC_2 & + & 2H_2O & \rightarrow & Ca(OH)_2 & + & C_2H_2 & \\ \text{Calcium carbide} & + & \text{Water} & & \text{Hydrated Lime} & + & \text{Acetylene} & (1) \end{array}$$

Despite the inherent challenges, the high $Ca(OH)_2$ content in CLW makes it a viable candidate for construction materials, with potential to reduce environmental impact [22]. While comprehensive studies on its direct application in mortar or concrete are still limited, CLW offers versatility, serving either as a primary binder or as an additive in plasters and mortars. Due to physical differences between waste-derived and conventional lime products, specific formulation adjustments are required. Both lime-based materials and CLW share $Ca(OH)_2$ as their primary component, which has a high CaO concentration, making it particularly effective for CO_2 capture. This composition allows lime-based materials, such as hydrated lime, to be produced directly from CLW, bypassing the need for energy-intensive processes like sintering, calcination, or digestion.

Aligned with the principles of transforming waste into valuable resources and promoting sustainability, this study utilizes CLW as a raw material for producing hydrated lime (HL). By facilitating the pozzolanic reactions and reducing CO_2 emissions, this approach not only encourages the use of CLW, but also promotes energy conservation. The investigation explored the performance of carbonation and compressive strength of CLW as a lime-based material when subjected to accelerated CO_2 curing during early curing stages. Limited research exists on the effectiveness of CLW under such conditions within a 24-hour period, highlighting a gap this study aims to address. Experimental tests were conducted under controlled conditions: a temperature of 60°C, relative humidity (RH) of 50-70%, and CO_2 concentration of 20% for varying durations within 24 hours. Additionally, Mercury Intrusion Porosimetry (MIP) was used to assess how optimised CLW impacts mortar porosity under accelerated CO_2 curing.

This study sheds light on the potential of CLW as a sustainable and eco-friendly material for the construction industry. The results contribute to the advancing knowledge on reducing the environmental impact of construction materials while efficiently reusing waste resources. These findings open new pathways for sustainable building practices, potentially influencing approaches to waste management and carbon capture in the concrete sector, and marking a step towards a greener, more sustainable future.

2. Materials and Methods

2.1 Materials

The materials used in this study included Ordinary Portland Cement (OPC), Carbide Lime Waste (CLW), fine aggregates, and tap water. The OPC and fine aggregate had densities of 3,150 kg/m³ and 1,576 kg/m³, respectively. The CLW was sourced from the northern region of Peninsular Malaysia, oven-dried at 105 °C for 24 hours to remove moisture and ensure a uniform and consistent texture. After drying, CLW was ground to pass through a 45 µm sieve, achieving a fineness comparable to OPC, where typically 85-95% of particles pass through the 45 µm sieve [23]. Particle Size Analysis (PSA) revealed that 99.73% of OPC particles and 92% of CLW particles met this standard. This reduction in particle size suggests CLW's potential as a viable cementitious alternative material.

Table 1 shows the chemical composition of OPC and CLW used in this study, with analyses conducted in southern Peninsular Malaysia. Fig. 1 provides an illustration of CLW. XRD findings, as shown in Fig. 2, show that the primary materials in CLW include portlandite, calcite, and graphite while the major minerals in OPC are C_3A, C_2S, C_3S, portlandite and calcite. The main mineral phase in finely ground CLW is $Ca(OH)_2$, with minor amounts of $CaCO_3$ and graphite. During prolonged storage, $Ca(OH)_2$ in CLW may react with ambient CO_2 to form $CaCO_3$, while graphite is a byproduct of CLW production.

Table 1 *Chemical composition of OPC and CLW*

Component	Percentages (%)	
	OPC	CLW
CaO	60.0	96.0
SiO_2	14.60	1.98
Al_2O_3	3.34	0.495
MgO	0.62	0.392
Fe_2O_3	2.20	0.302
TiO_2	0.21	0.0252
MnO	-	0.0063
SO_3	2.63	0.022

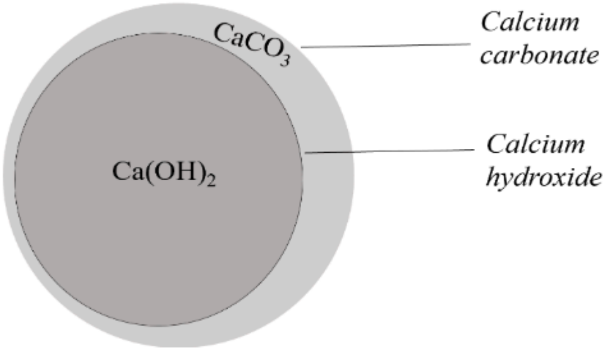


Fig. 1 *The illustration of particle composition of ground carbide lime waste (CLW)*

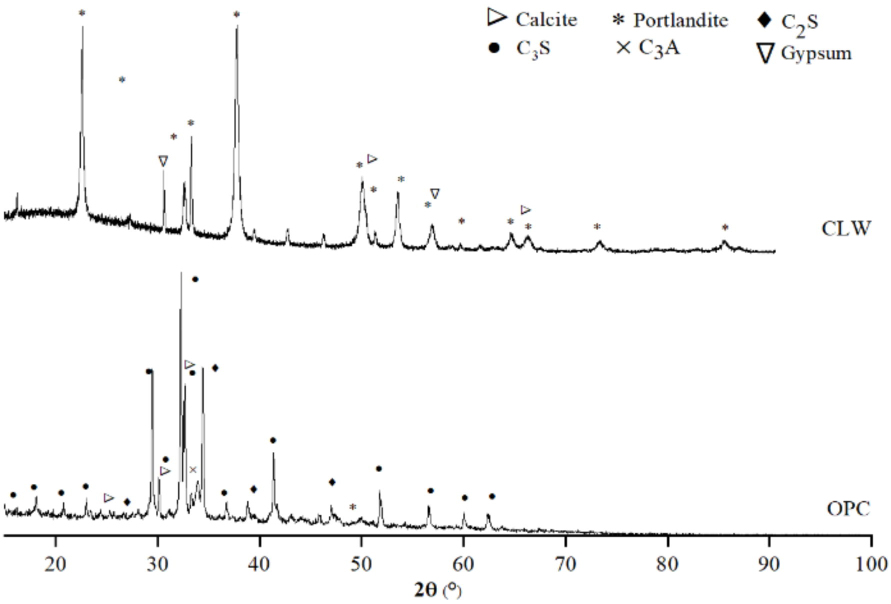
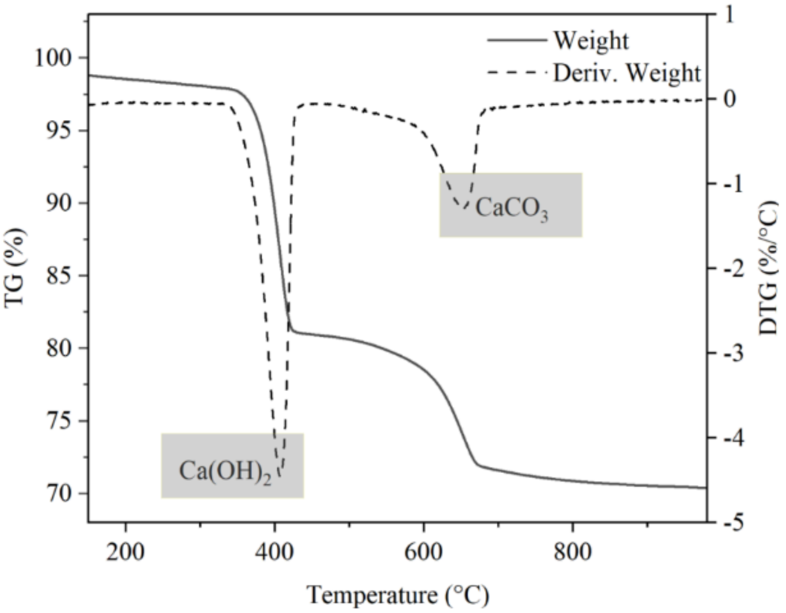
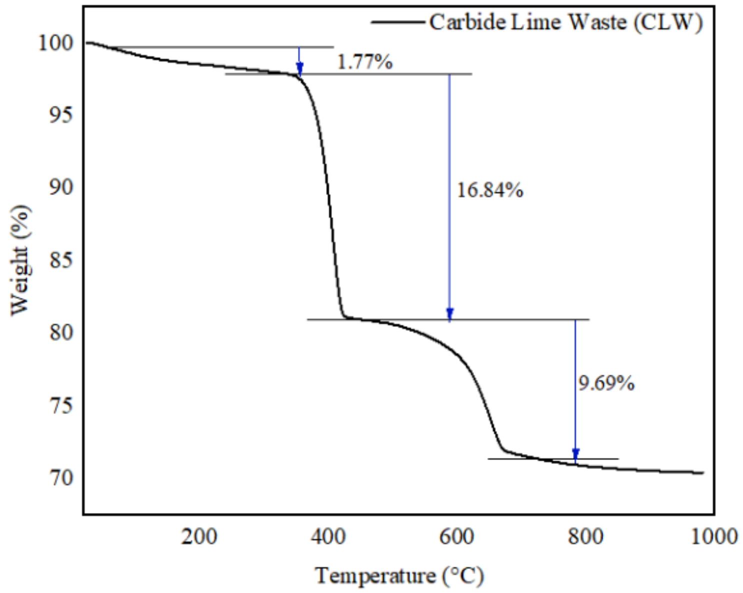


Fig. 2 *XRD for ground CLW and OPC*

Thermogravimetric analysis (TGA) was used to further examine the composition of CLW, primarily consisting of $Ca(OH)_2$ with trace amounts of $CaCO_3$. Fig. 3(a) shows three significant peaks. The first peak was associated to a weight loss between 60 – 350°C due to the evaporation of free water as well as the breakdown of CSH and Aft phases. The second peak, occurred between 350 – 600°C, was attributed to the breakdown of $Ca(OH)_2$ with a 16.84% weight loss; this phase transition can be described as $Ca(OH)_2 \rightarrow CaO + H_2O$. The third endothermic peak, occurred at over 600°C, indicated the disintegration of $CaCO_3$ with a mass loss of 9.69% as shown in Fig. 3(b). These results confirm that $Ca(OH)_2$ is the primary component in CLW, containing a high CaO content, which is highly effective for CO_2 capture.



(a)



(b)

Fig. 3 *TGA analysis of ground CLW (a) TG-DTG curve; (b) Mass loss percentages*

2.2 Sample Preparation

After finalizing the material mixing proportions, as presented in Table 2 [24], the mortar was carefully poured into moulds of two different dimensions: (50 x 50 x 50 mm) and (40 x 40 x 160 mm). Each mould was filled in two layers after mixing. To ensure proper compaction, the moulds were vibrated for 10 seconds per layer. The tops were levelled for uniform load distribution, minimizing potential measurement errors in strength testing. To prevent evaporation, the cast samples were covered with plastic sheet and kept at room temperature.

Table 2 *Mix design proportion*

Types of mortar	Cement (kg/m^3)	CLW (kg/m^3)	Sand (kg/m^3)	w/c
Control	5200	0	5328	0.6
10% CLW	4680	520		
20% CLW	4160	1040		
30% CLW	3540	1560		
40% CLW	3120	2080		

After 24 hours, the samples were demoulded and placed in a controlled CO_2 chamber for accelerated curing. The chamber, equipped with a safety valve and pressure gauge, was connected to a CO_2 gas tank cylinder containing 98% purity CO_2. The gas was injected at a pressure of 15 psi, creating curing conditions of 60°C, 70±5% RH and a CO_2 concentration of 20%. Sample parameters – workability, density, compressive strength, carbonation thickness, and CO_2 uptake – were measured at curing intervals of 1, 3, 6, 10, 13, 16, 20 and 24 hours. This comprehensive assessment allowed for the determination of the optimal CLW mortar composition with the desired properties. Finally, the porosity of the optimal CLW mortar was analysed and compared to that of the control mortar.

2.3 Testing Procedure

2.3.1 Flow Table

The flow table test assessed the impact of hydrated lime on the fluidity of CLW mortar. After thorough mixing, ingredients were layered twice in moulds and each layer was tamped 20 times to ensure uniformity. Excess mortar was trimmed using a trowel. The moulds was then lifted, and the table was dropped 25 times within 15 seconds, following the ASTM-C1437 standard [25].

2.3.2 Apparent Density

An electronic digital balance was used to determine the apparent density of control and CLW mortars at hardened state prior to and following each CO_2 curing age. The weight of the samples was measured after demoulding and curing. Then, the weight was divided by the volume to obtain the density of each sample [26].

2.3.3 Compression

The compressive strength was determined from the compression test by using 50 x 50 x 50 mm cube samples, following the ASTM C109 standard [27]. Eight different CO_2 curing duration were tested; 1, 3, 6, 10, 13, 16, 20 and 24 hours. Average strength was calculated from these measurements, using a Universal Testing Machine with a 3000 kN capacity at a loading rate of 2000 N/s. A total sample size of 168 cubes were testing. The targeted strength is based on the mortar application as stated in the standard [24].

2.3.4 Visual Carbonation Thickness Evaluation

Carbonation thickness was visually assessed using a phenolphthalein spray test on fractured prism surfaces. The prism samples were broken into two sides, and the fracture surface was cleaned using a brush to remove any dust. A split mortar prism was then sprayed with 1% phenolphthalein alcohol solution to determine the carbonation depth of the concrete. The carbonation thickness was determined by averaging the measurements from ten points across the sample's cross-section [28].

2.3.5 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was performed to determine the amount of $CaCO_3$ precipitation in control and CLW mortar under accelerated CO_2 curing conditions. For each TGA test, the control and CLW pastes were prepared and demoulded after 24 hours. Then, the pastes were immersed in acetone solution for 24 hours to stop hydration and then dried completely at 105°C for a day. Before the examination, the dried samples were crushed into a powder form with a particle size less than 45 µm [29]. About 5 to 10 mg of the powder were loaded and heated at a rate of 10°C/min from 25°C to 1000°C in the presence of flowing N_2 gas.

2.3.6 Mercury Intrusion Porosimetry (MIP)

Mercury Intrusion Porosimetry (MIP) is one of the most common techniques used to analyse the pore structure characteristics of cementitious materials. This technique injects mercury into a sample and determine the volume of pores based on the quantity of mercury infused. MIP was conducted to investigate the microstructural characteristics of pore size diameter on both the control and optimum CLW mortars after 24 hours of CO_2 curing. The paste samples that were used for MIP were immersed in acetone to stop hydration and oven-dried for 24 hours to obtain a uniform sample. The samples were subjected to low (up to 5 psi) and high (up to 30,000 psi) mercury pressures to measure microporosity. Pore characteristics were evaluated to observe the micro-filling effect of CLW and its influence on porosity [30].

3. Results and Discussion

3.1 Workability

The addition of CLW to cement mortar reduced flowability, as indicated in Table 3. This reduction is due to CLW's ability to disperse cement particles, which limits mortar fluidity [31]. The presence of additional hydrated lime in the mixture also slightly inhibited cement hydration by consuming mixing water to produce crystallized phases with high-temperature stability [32]. Lime, being less reactive than cement and contributing to reduced gel formation, tends to affect the workability of the mortar. The 30% CLW mortar mix met standard workability requirements (110±5%), providing suitable uniformity and bonding.

Table 3 *Workability of CLW mortar with various proportions*

CLW (%)	10	20	30	40
Workability (%)	143.0	133.2	110.7	95.0

3.2 Apparent Density

Fig. 4 illustrates the impact of carbonation age time on the apparent density of the samples under CO_2 curing. The apparent density of all samples decreased with increasing CO_2 curing duration, with further reductions observed as CLW content increased. Notably, the apparent density of the 10% CLW mortar was 2.4% higher than control mortar. This difference can be attributed to the hydration products and additional calcium carbonate ($CaCO_3$) precipitation in the CLW mortar. The formation of $CaCO_3$ likely filled some of the pores in the mortar matrix, making it slightly denser. However, prolonged curing led to density reductions in all mortars.

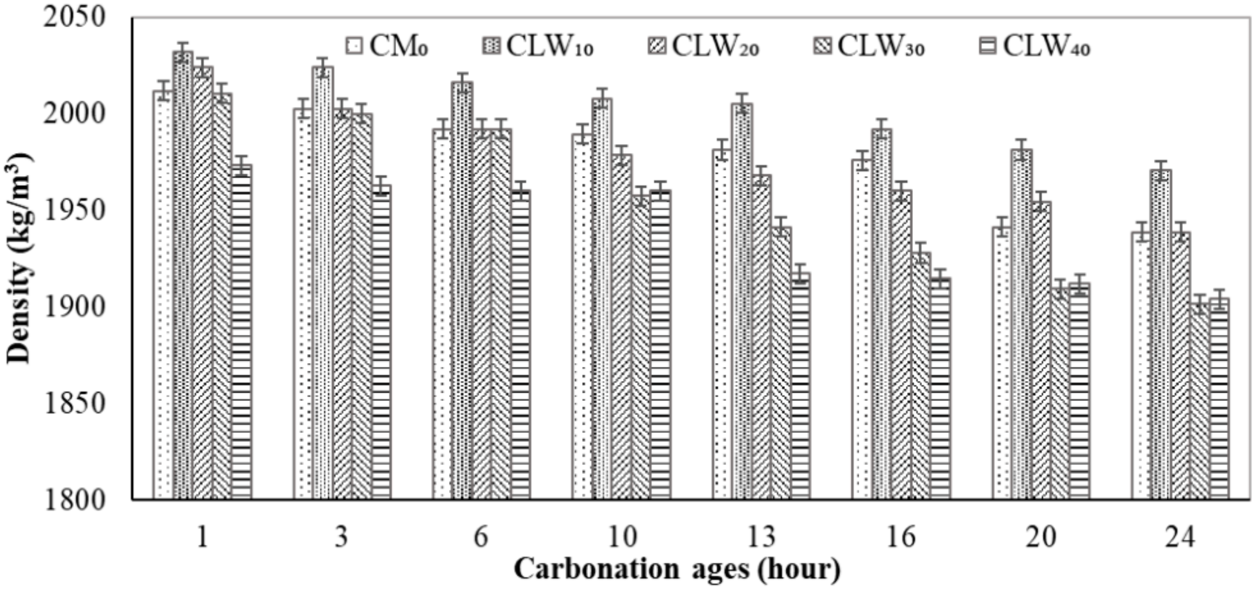


Fig. 4 *Density of control and CLW mortar at various durations*

The reaction of $Ca(OH)_2$ with CO_2 produces $CaCO_3$ and water. $CaCO_3$ precipitates within the mortar, but elevated curing temperatures cause water evaporation, which contributes to density loss. This aligns with findings from previous studies, where elevated temperature between 20°C and 800°C reduced density across samples [9], [33]. The most significant density loss is attributed to the evaporation of free water and the loss of hydrated bound water due to the decomposition of ettringite (AF_t) and CSH gel derived from auto-cleaving cement hydration. Decomposition of $Ca(OH)_2$ is primarily responsible for the density reduction at this temperature. The higher the CLW content, the more $Ca(OH)_2$ is added to the mixes, and this further decreases the density of the mortar. Additionally, since CLW has a lower specific gravity than OPC, increasing CLW content results in lighter mortars [18].

3.3 Compressive Strength

Fig. 5 illustrates compressive strength improvements in CLW mortar with extended CO_2 curing, especially within the first six hours and followed by a marginal improvement thereafter. However, it is noteworthy that the compressive strength after 16 hours was significantly lower than the strength achieved within the first six hours. Among all the mixes, the 10% CLW mortar exhibited the highest strength within 24 hours, surpassing the control mortar's strength. Within the first six hours, the strength improved 8% and reached almost 50% of its total strength. This can be attributed to the carbonation of minerals such as C_3S and β -C_2S present in dehydrated cement particles, which easily react with CO_2 during the early stages [32]. The strength performance of both control and 10% CLW mortar improved approximately 108% and 98%, respectively, within 24 hours. This significant increase in strength during the early stages indicates the effectiveness of the CO_2 curing process for all mixes.

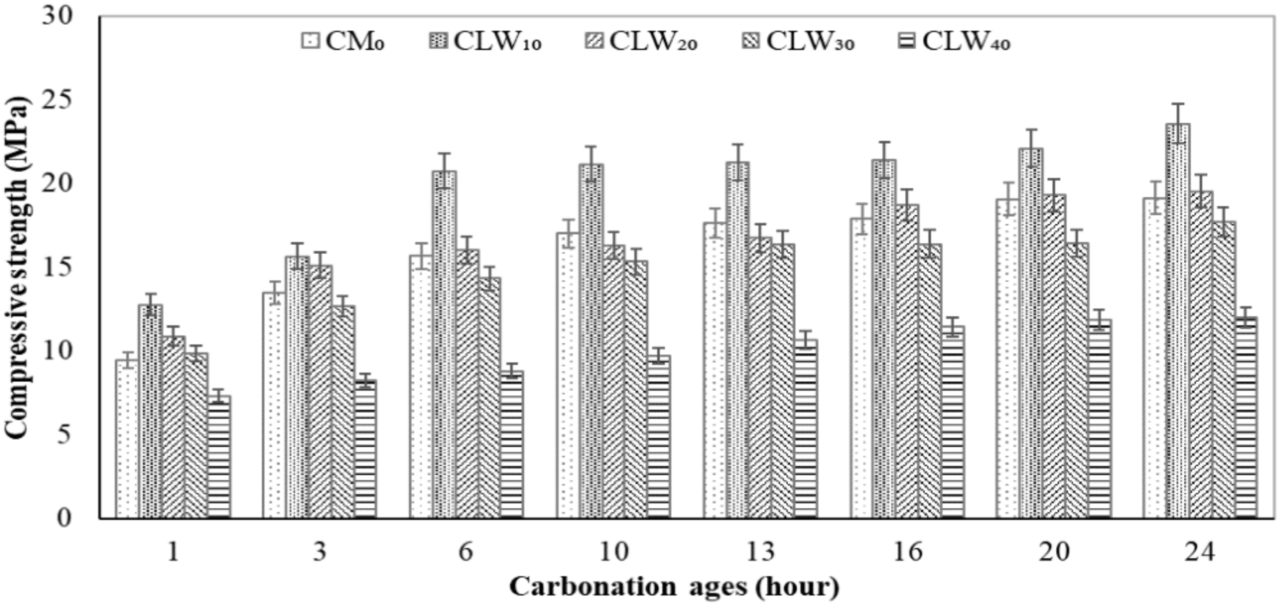


Fig. 5 *Compressive strength of control and CLW mortar mixes at various durations*

Strength gains were steady across all mortars. The 10% mortar showed the highest compressive strength and the 20% CLW mix slightly exceeded the control. In contrast, the compressive strength of 30% and 40% CLW mortars were lower than control, though the 30% mix still met the requirements for both load- and non-load-bearing applications. The 40% CLW mortar, however, failed to meet desired workability and showed the lowest strength, likely due to an insufficient w/c ratio for adequate hydration. The water shared between cement and CLW in the pozzolanic reaction suppressed cement hydration, and higher CLW content resulted in a looser matrix with few hydration products, weakening the mortar's mechanical properties [34]. The dilution effect from increased CLW further reduced compressive strength, as bonding agents in the mix were reduced [35].

However, under accelerated CO_2 curing conditions, carbonation time enhanced the compressive strength of the mortar due to the availability of calcium hydroxide $Ca(OH)_2$ in the mortar from both cement and CLW, which contributed to pozzolanic reaction. The strength increase is linked to the greater volume of $CaCO_3$ formed compared to $Ca(OH)_2$ during carbonation [36]. This finding aligns with previous research on the impact of admixture reactivity and $Ca(OH)_2$ content on the mechanical and durability properties of mortar and concrete [32].

In general, the compressive strength of mortars decreased with an increase in CLW content, consistent with findings from previous studies [37]. This behaviour can be attributed to the lower cementitious behaviour of CLW compared to cement, leading to a less dense binder structure [38]. When CLW content exceeds a certain threshold, the availability of active silica for pozzolanic reactions becomes insufficient, causing excess $Ca(OH)_2$ to dissolve, which increases porosity and reduces mechanical properties [32]. In this study, an accelerated carbonation curing regime was adopted to enhance the mechanical properties, and it is proven effective in enhancing the compressive strength of all mixes within the first 24 hours. The increase in strength is attributed to the formation of carbonation products and a reduction in porosity, resulting in improved strength [39].

3.4 Carbonation Thickness

Fig. 6 presents the carbonation thickness of control and CLW mortars with varying proportions under controlled CO_2 curing conditions. The results indicated that carbonation thickness increased with extended curing time. The addition of CLW introduced a higher amount of portlandite. Generally, in Supplementary Cementitious Materials (SCMs), the addition of SCMs reduces the amount of portlandite in the mix. The carbonation process then transforms the portlandite into $CaCO_3$. This study specifically investigated how direct CLW addition affects carbonation behaviour.

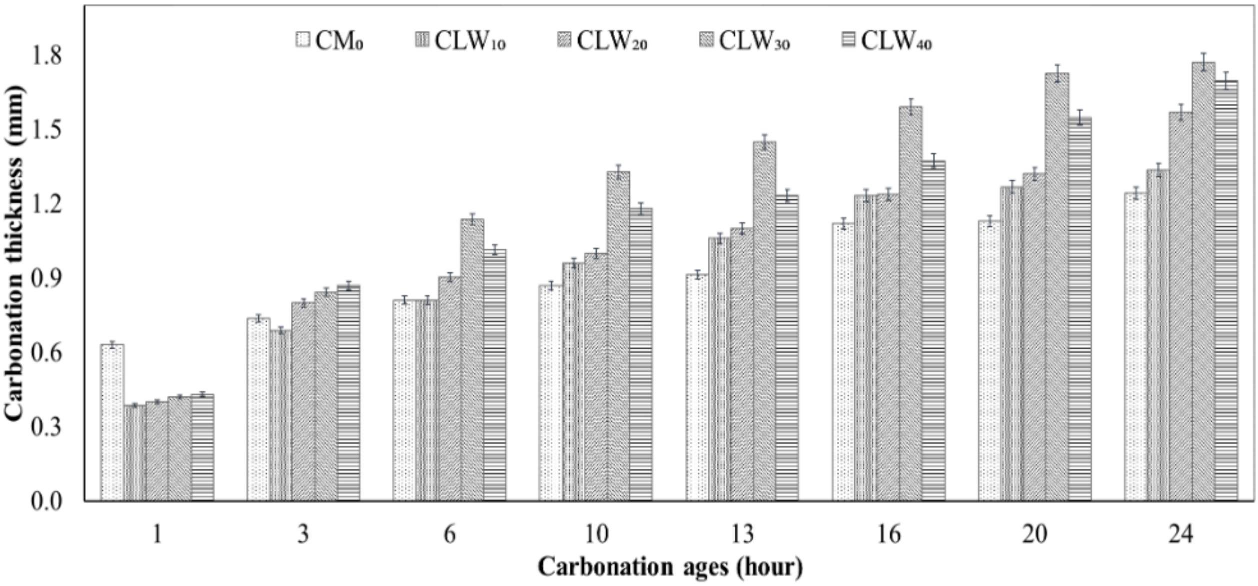


Fig. 6 *Carbonation thickness of control and CLW mortar mixes at various duration*

In the early carbonation phase, the control mortar exhibited the highest carbonation rate at 1 hour, achieving a CO_2 capture thickness of 0.63 mm. This rapid carbonation rate in the control mix during the first three hours is attributed to the higher activity of alite hydration, which quickly generates $Ca(OH)_2$. Consequently, mortars without added hydrated lime initially carbonated faster than mortars with added CLW, benefiting from newly generated $Ca(OH)_2$ [37].The presence of CLW in the mortar influenced its initial ability to capture CO_2, as CLW partially suppressed cement hydration and consumed some of the mixing water with cement [32].

However, from 6 to 24 hours, the 30% CLW mortar achieved the highest CO_2 capture, with carbonation thickness ranging from 1.14 to 1.77 mm, outperforming the control and other CLW mixes. The 30% CLW mortar also showed a good carbonation thickness consistency, compared to the variability seen in other mortars. Despite the accelerated carbonation conditions, reactions with hydration products such as CSH gels, $Ca(OH)_2$ and ettringite (AF_t) were minimal, as CO_2 primarily reacted with silicate phases (C_2S and C_3S) [40] in cement. However, $Ca(OH)_2$ from CLW materials enhanced the performance of CO_2 capturing. This finding highlights that CLW addition progressively impacts carbonations, with carbonation performance accelerating notably after six hours of curing. During the initial hour of curing, the carbonation reaction occurred rapidly, and the presence of CLW played a significant role in enhancing the process.

Moreover, the carbonation rate was found to be influenced by the water-to-cement (w/c) ratio. The carbonation thickness increased with increasing w/c ratio while keeping the carbonation time constant. A high w/c ratio and high porosity contributed to the diffusion of CO_2 and improved carbonisation efficiency. This is consistent with previous research that tested various w/c ratios in the range of 0.3 to 0.6 and found an increased carbonation rate with higher w/c ratios for OPC paste [41]. In this study, the high w/c ratio of 0.6 appears to support carbonisation by enhancing porosity, allowing better CO_2 transmission and distribution within the hardened paste. Additionally, increased carbonation thickness can be attributed to higher porosity resulting from the evaporation of free water in the mortar.

3.5 $CaCO_3$ Precipitation

Fig. 7 illustrates the $CaCO_3$ precipitation in control and CLW pastes under CO_2 curing conditions after 24 hours. Two peaks of mass loss were observed in both the control and CLW mortars at 350-500°C and 600-750°C, corresponding to the decomposition of $Ca(OH)_2$ and $CaCO_3$, respectively. As $Ca(OH)_2$ reacted with CO_2, the $Ca(OH)_2$ peak disappeared, leading to a notable increase in the $CaCO_3$-related peak. Table 4 shows the total $CaCO_3$ formed in control and CLW pastes after CO_2 curing.

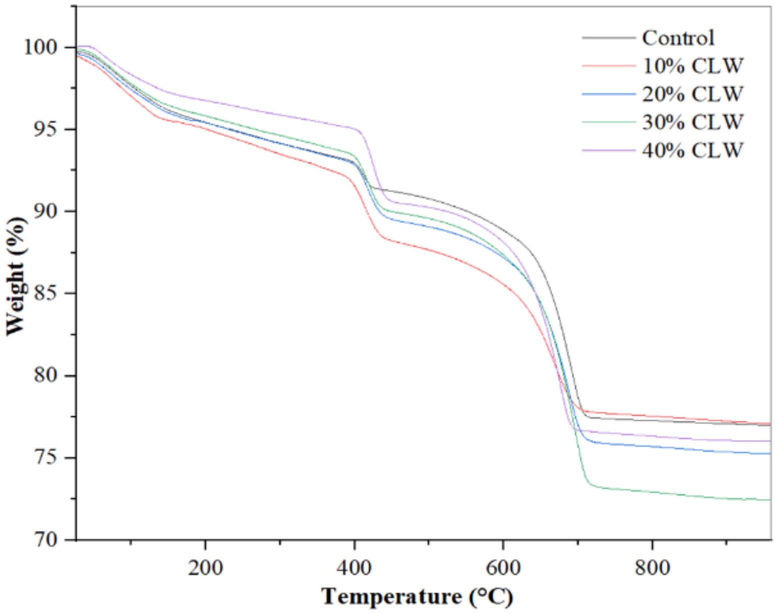


Fig. 7 *TGA performance under various CLW percentages at 24 hours*

Table 4 *$CaCO_3$ precipitation after 24 hours of curing*

	CO_2 concentration (%)	Temperature (°C)	$CaCO_3$ (%)
Control	20	60	28.15
10% CLW			19.07
20% CLW			26.32
30% CLW			34.61
40% CLW			34.22

The 30% CLW showed the highest $CaCO_3$ precipitation, suggesting that CLW accelerated the carbonation process due to the presence of $Ca(OH)_2$. In contrast, the 10% CLW mortar had the lowest CO_2 capture at approximately 19.07%, although this increased in the 20% CLW sample. This improvement can be attributed to the micro-filling effect of hydrated lime in the 20% CLW mortar, enhancing particle size distribution and microstructure.

When comparing CLW mortars to the control, mortars with 30% and 40% CLW showed $CaCO_3$ increases of 22.9% and 21.6%, respectively. In high CO_2 concentration environments, carbonation reactions in cement-based materials are prioritized over hydration, leading to rapid $CaCO_3$ precipitation and formation of calcium-modified silica gel; this results in changes in chemical and mineralogical compositions [42]. After the 30% CLW peaked, carbonation decreased with further CLW additions, likely due to a denser structure that limited carbonation [9].

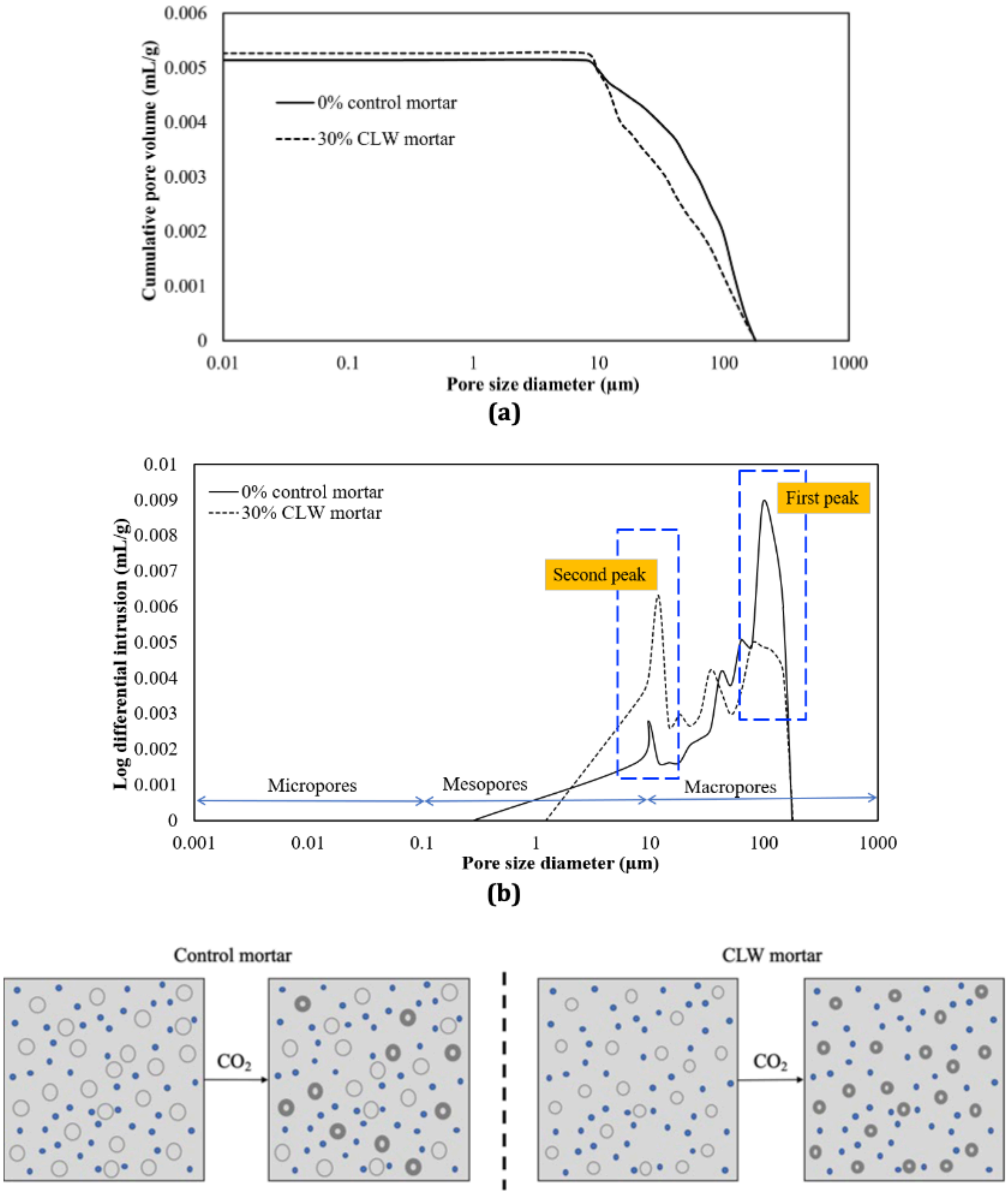
This finding contrasts with a previous study where rapid strength gains in CO_2-cured samples were attributed to a robust carbonated surface layer formed during the carbonation process. In this study, the results from TGA and carbonation thickness measurement indicated that the highest compressive strength was in the 10% CLW mortar, while the 30% CLW mortar exhibited the highest carbonation thickness. This discrepancy may be influenced by the w/c ratio, which influences mortar workability. The 0.6 w/c ratio used in the 30% CLW mortar provided sufficient water for effective carbonation during hydration and curing. Adequate water facilities carbonation, though excessive water can obstruct the permeation tunnel and reduce CO_2 absorption [32], [43].

3.6 Porosity

The effects of CO_2 carbonation curing on pore structure in both control and optimum 30% CLW mortars after 24 hours were analysed using Mercury Intrusion Porosimetry (MIP). Fig. 8 presents the cumulative pore volumes and log differential intrusion for control and 30% CLW mortar. As depicted in Fig. 8a, there are only minor differences in the pore size distribution. Pore sizes were categorised into four ranges: micropores (4.5 nm), mesopores (4.5–50 nm), middle capillary pores (50–100 nm), and large capillary pores (>100 nm) [32]. As seen in Fig. 8b,the control mortar has a slightly higher volume of large pores.

At the first intrusion peak, the control mortar showed higher mercury intrusion within the pore diameter range of 97.78 µm, whereas the 30% CLW mortar displayed a diameter of 78.60 µm. At the second peak, the 30% CLW mortar exhibited maximum intrusion at a pore diameter of 11.92 µm, compared to 9.70 µm in the control mortar. Consequently, the control mortar displayed the largest capillary pores (macropores), with a maximum mercury intrusion of 0.009 mL/g, while the 30% CLW mortar showed an intrusion value of 0.0063 mL/g at the second peak.

In general, accelerated carbonation enhanced the porosity of the CLW mortar, particularly at the first peak, where pore size difference between control and CLW mortars were notable. The addition of hydrated lime had a micro-filling effect that improved particle size distribution and microstructure [32], resulting in a refined microstructure of the mortar after 24 hours of CO_2 curing [15]. The accelerated carbonation rate of hardened materials was significantly impacted by pore size distribution and porosity, with the w/b ratio influencing the distribution of pore sizes and porosity [41]. Fig. 8c illustrates the reduction in porosity and refinement of pore size distribution in control and 30% CLW mortars under CO_2 curing, as seen in Fig. 8b. This refinement is primarily attributed to the formation of $CaCO_3$ [28], [39], [44].



(a)

(b)

(c)

Fig. 8 *Porosity of control and CLW mortar at 24 hours (a) Cumulative pore volume; (b) Log differential intrusion; (c) Illustration* sketch *on the porosity enhancement*

4. Conclusions

To enhance the carbonation activity of CLW, grinding was employed to achieve a particle size comparable to cement. This study examined the effects of a w/c ratio of 0.6, a 20% CO_2 concentration, and relative humidity (RH) of 50-70% on the CO_2 absorption and mechanical properties of CLW under accelerated CO_2 curing for 24 hours. The key findings are summarized as follows:

- **Fresh Properties:** Increasing CLW content reduced the workability of CLW mortars, primarily due to CLW's high water absorption. Among all CLW mixes, 30% CLW mortar mix achieved the standard-specified workability, making it a suitable choice for practical applications.
- **Mechanical Properties:** The mortar with 10% CLW showed the highest compressive strength. This is attributed to the reaction of alite and belite in cement with $Ca(OH)_2$, which reacted with CO_2 to strengthen the mix. However, the strength decreased as CLW content exceeded 10% due to reduced CSH gel formation that plays a significant role in strength development.
- **CO_2 Absorption and Physical Properties:** The 30% CLW mortar met desired standards for workability, mechanical strength, and CO_2 capture. TGA results confirmed that this mix had the highest CO_2 absorption capacity within 24 hours, effectively capturing CO_2 early in the curing process. Furthermore, the mixture achieved the desired load- and non-load-bearing strength requirements within 24 hours under accelerated CO_2 curing.
- **TGA Analysis:** TGA results showed a significant conversion of $Ca(OH)_2$ to $CaCO_3$ in the 30% CLW mortar within 24 hours of CO_2 curing. As a stable source of $Ca(OH)_2$, CLW effectively enhanced CO_2 storage in mortar, demonstrating strong early-age CO_2 capture performance compared to the control.
- **Porosity Improvement (MIP Analysis):** MIP analysis revealed that accelerated CO_2 curing improved the porosity of CLW mortars, particularly in the 30% CLW mix, which exhibited reduced pore sizes compared to the control. This concluded that the use of CLW materials as an alternative to cement materials can enhance not only the mechanical properties, but also the porosity through CO_2 sequestration under accelerated CO_2 curing.

Aligned with the global Sustainability Development Goals (SDGs), CLW presents a promising solution as a CO_2 absorbent material capable of producing building materials with exceptional mechanical properties. This innovative approach not only repurposes industrial waste, but also contributes to CO_2 sequestration, supporting sustainable development in the construction industry.

Acknowledgement

The authors are grateful for the financial support provided by Universiti Teknologi Malaysia under university's grant with registration numbers R.J130000.7622.4C806 and Q.J130000.3822.22H88. Additionally, the authors extend their appreciation to the Mineral Research Centre, Minerals and Geoscience Department Malaysia, and the ASEAN-ROK Award for Excellence in Science, Technology and Innovation Korea for their invaluable encouragement and support throughout this research.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nur Hafizah A. Khalid, Abdul Rahman Mohd.sam;* ***material selections****: Rohaya Othman;* ***data collection:*** *Adrina Rosseira A. Talip, Zahraa Hussein Joudah;* ***analysis and interpretation of results:*** *Adrina Rosseira A. Talip, Nur Hafizah A. Khalid, Abdul Rahman Mohd.sam;* ***draft manuscript preparation:*** *Adrina Rosseira A. Talip, Nur Hafizah A. Khalid. All authors reviewed the results and approved the final version of the manuscript.*

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