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Research Article

Influence of Mineral Admixtures on the Properties of Magnesium Oxychloride Cement Lean Concrete

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This study investigated the effects of light-burned magnesia, fly ash (FA), dolomite powder (DP), and limestone powder (LP) contents on the performance of magnesium oxychloride cement lean concrete (MOCLC). The effects of light-burned magnesia and mineral admixture content on the mechanical properties and durability of MOCLC were tested by the compressive strength test, splitting strength test, water resistance test, shrinkage test, and fatigue test, respectively. The results revealed that the optimum dosage of MgO was 4%. The optimum dosages of FA, DP, and LP were 25%, 20%, and 20% of the cement dosage, respectively. The compressive and splitting strengths of the MOCLC were decreased by the addition of FA and DP. Due to part of the internal pores of MOCLC were filled with FA and DP, the decomposition of the main strength phase $5Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O$ (phase 5) was suppressed and the water resistance of MOCLC was improved. The addition of FA and DP also improved the shrinkage resistance, and the fatigue resistance of MOCLC was also improved by the addition of FA and DP. The water resistance, shrinkage, and fatigue properties of MOCLC with a FA content of 25% were better than those of MOCLC with DP and LP.

1. Introduction

Lean concrete (LC) has attracted significant attention owing to its low cement content, high strength, and excellent frost resistance [1, 2]. However, previous studies have shown that LC composed of ordinary silicate cement suffers from low early strength and slow strength development [3–5]. The primary reason for this is that ordinary Portland cement has a sluggish hydration rate and a high hydration heat release rate, which results in significant hydration heat release.

Compared with ordinary Portland cement, magnesium oxychloride cement (MOC) has a good availability, simple preparation [6, 7], low energy consumption, high early strength, and excellent adhesion with a variety of materials [8–10]. MOC is a gas rigid gelled material that was invented by the French chemist Sorel in 1867, and it was made of $MgCl_2$ solution and active magnesium oxide powder [11]. The mixture of active magnesium oxide powder and magnesium chloride solution will produce an exothermic chemical reaction, and MOC with excellent mechanical properties will be rapidly formed [12, 13]. The MOC system is a typical ternary system produced from the reaction of magnesium oxide, magnesium chloride, and water [14, 15]. The chemical expression of the ternary system is MgO-

$MgCl_2$-H_2O. The mechanical properties of MOC depend upon its hydration products [16, 17]. Generally, at ambient condition phases, the main hydration products of MgO-$MgCl_2$-H_2O are $5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$ (phase 5) and $3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$ (phase 3) [18]. The formation of phases 5 and 3 of MOC is summarized in the following equation:

$$\begin{aligned} 5MgO + MgCl_2 \cdot 6H_2O + 7H_2O &\longrightarrow 5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O, \\ 3MgO + MgCl_2 \cdot 6H_2O + 5H_2O &\longrightarrow 3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O, \end{aligned} \tag{1}$$

Phases 5 and 3 of MOC occur as well-crystallized needles that developed quickly and have a high material strength. In further detail, phase 5 is almost completed after 96 h and phase 3 is almost completed after 36 h. The crystallized needles can be described as scroll-tubular whiskers. Whiskers intergrow into structures with higher density, which is the key reason for MOC strength growth. Although the thermal stability of phases 5 and 3 is low, and they start to decompose at 145°C and 125°C, respectively, to form H_2O and HCI, they can exist stably at ambient temperature [19, 20]. Therefore, phases 5 and 3 are also called the main strength phases of the MOC system. Reportedly, the mechanical properties and durability of concrete can be effectively improved by adding MOC to concrete materials [21, 22]. As a cementitious material for the preparation of concrete, MOC has a particularly prominent advantage of strength. Zheng et al. investigated the mechanical characteristics of magnesium oxychloride cement concrete (MOCC) using the changing law of the microstructure. The addition of MOC increases the pavement strength of the structure, which was based on X-ray diffraction (XRD) and scanning electron microscopy (SEM) results, as well as the compressive and flexural strengths of MOCC at various ages [23]. Cheng et al. investigated the long-term mechanical properties of MOCC, measured the change in the phase 5 content in MOCC by XRD and SEM, and tested the compressive strength of MOCC at 28, 180, and 270 days. It has been found that the long-term strength of MOCC is significantly higher than that of the ordinary concrete of the same grade [24]. Notably, the early strength properties of MOCC are also excellent. According to Hao and Li, the early strength is higher because MOCC has a greater interfacial adhesion than ordinary concrete [25]. In addition to its mechanical properties, MOCC also exhibits excellent durability. Generally, concrete construction in saline environments can be harmed by salt. However, Gong et al. found that high Mg^{2+} and Cl^- concentrations would enhance the development of phase 5, ensuring the structural integrity and endurance of the MOCC [26]. Although the addition of MOC to concrete buildings can significantly increase their mechanical and durability features, water resistance issues still exist [27, 28]. Phases 5 and 3 are easy to decompose in the water environment, and the strength of MOC decreases gradually [23]. The specific decomposition formula is shown in equations (2) and (3).

$$5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O \longrightarrow 5Mg(OH)_2 + Mg^{2+} + 2Cl^- + 8H_2O, \tag{2}$$

$$3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O \longrightarrow 3Mg(OH)_2 + Mg^{2+} + 2Cl^- + 8H_2O. \tag{3}$$

Mineral admixtures have been used to increase the water resistance of MOCC. Qiao et al. studied the effects of phosphoric acid and fly ash (FA) on the water resistance of MOCC by analyzing the water resistance coefficient of MOCC after soaking for 90 days. Combined with different soaking conditions, the study found that water resistance can be effectively improved by phosphoric acid and FA [29]. Furthermore, Deng et al. reported that the coordination of phosphate and magnesium ions increased the water resistance of MOCC [30]. Moreover, the pores and cracks in concrete can also be filled with fibers, which increase the water resistance coefficient, thus improving its water resistance [31].

In summary, existing research studies primarily focus on enhancing the strength and durability of concrete using MOC. Mineral admixtures, such as FA and phosphoric acid, have been used to enhance the mechanical strength and durability of concrete. However, there has currently been little research reporting the application of MOC in lean concrete. In addition, the effects of FA, DP, and LP on the water resistance and durability of MOCLC have not been studied. As lean concrete is mainly used for road bases, its material composition and strength evaluation index are different from ordinary concrete. As a result, the existing conclusions of adding MOC to concrete cannot be directly applied to MOCLC. Based on the above considerations, this paper uses MOC to prepare lean concrete instead of ordinary Portland cement. The effects of different magnesium cement contents and mineral admixtures on the mechanical properties and durability of LC were studied through compression, splitting, immersion, shrinkage and fatigue tests, and microscopic analysis. The addition of MOC can not only improve the early strength of lean concrete but also reduce the cement consumption. The addition of mineral admixtures has little effect on the mechanical properties of MOCLC, but it can effectively improve the water resistance

Table 1: Chemical composition of lightly burned magnesium oxide powder.

Oxide	MgO	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	Fe_2O_3	P_2O_5	TiO_2
Mass fraction (%)	80.21	6.87	2.01	1.58	0.22	0.15	1.32	0.21	0.02

Table 2: Basic properties of lightly burned magnesium oxide powder.

Size		Setting time		Fineness	Stability
Grain size (μm)	Specific surface area (m^2/g)	Initial setting (min)	Final setting (h)	170 mesh screen allowance (%)	
70	30.2	>40	<7	<25	Qualification

Table 3: Chemical compositions of magnesium chloride hexahydrate.

Material	$MgCl_2{\cdot}6H_2O$	NaCl	KCl	$CaCl_2$
Mass fraction (%)	96.4	0.3	0.7	0.2

and durability of MOCLC. It can be seen that the application of MOC in lean concrete is expected to achieve an energy-saving green base.

2. Materials and Test Methods

2.1. Raw Materials. The raw materials used for preparing the magnesium oxychloride cement lean concrete (MOCLC) included light-burned magnesia, magnesium chloride hexahydrate, mineral admixtures, and coarse and fine aggregates. The magnesia employed in this study was 80.3% pure with 57% activity. It was obtained from Yingkou Huiteng refractory material Ltd. (Liaoning Province, China). The chemical compositions and basic properties are shown in Tables 1 and 2. Magnesium chloride hexahydrate ($MgCl_2{\cdot}6H_2O$) was obtained from Yuze Chemical Ltd. (Shandong Province, China). Its chemical composition is shown in Table 3, in which the content of magnesium chloride is 45% and the water content is 50%. Continuously graded limestone rubbles meeting the requirements of Chinese standard GB/T 14685-2011 [32] were applied as coarse aggregate and their size range was from 5 mm to 25 mm. The water absorption and specific gravity of gravel were 0.68% and 2.72, respectively. The crushing value of gravel is 6.8%. Moreover, the water absorption and specific gravity of sand were found to be 1.24% and 2.63, respectively. The sand was the river sand with a fineness modulus of 2.6 while FA, dolomite powder (DP), and limestone powder (LP) were incorporated in the proportions of 10%, 15%, 20%, 25%, and 30%, respectively, by mass of MOC. FA, DP, and LP were obtained from, respectively, Xi'an power plant, Jiangxi Sanbao Industry and Trade Co., Ltd., and Beijing Hongwei Yongjia building materials Co., Ltd. FA with silica and alumina of 87% (Class *F*). The chemical compositions of the FA, DP, and LP are shown in Table 4. In accordance with the Chinese standard JGJ 63–2006 [33], ordinary tap water was used for the tests.

The content of magnesium oxide was divided into 3%, 3.5%, 4%, 4.5%, and 5%, numbered $MOCLC_1$, $MOCLC_2$, $MOCLC_3$, $MOCLC_4$, and $MOCLC_5$ respectively, to study the effect of lightly burned magnesia content on the performance of MOCLC. The mixing proportions of MOCLC are shown in Table 5. MOCLCs with different mineral admixtures are denoted as MOCLC-FA, MOCLC-DP, and MOCLC-LP.

2.2. Specimen Preparation. The specimen preparation included seven steps. (1) Preweighed water and magnesium chloride hexahydrate were poured into the glass in turn, and the magnesium chloride solution was prepared by stirring thoroughly for 2 mins using a glass rod. The MOC was prepared by pouring preweighed lightly burnt magnesium powder into magnesium chloride solution and stirring it thoroughly with a glass rod for 5 mins. (2) Then, the preweighed mineral admixture was poured into MOC and was mixed with a glass rod evenly for 5 mins. (3) Preweighed raw materials (sand and gravel) were poured into the basin and mixed evenly with a spatula for 2 mins. (4) The mixtures from (2) and (3) were mixed with a shovel for 5 mins. (5) The slump of the MOCLC was measured according to the Chinese standard JTG 3420-2020 [34]. (6) The MOCLC was cast in 150 mm × 150 mm × 150 mm and 100 mm × 100 mm × 400 mm steel dies, which were cured for 24 h in an indoor natural environment (the temperature and the relative humidity were 22 ± 5°C and 65 ± 5%, respectively). During the curing process, a film was used to cover the steel dies containing the specimen. (7) MOCLC was removed from the steel dies and then cured for 3 days, 7 days, 14 days, 28 days, and 90 days at a temperature of 20 ± 2°C and a relative humidity above 95%, respectively.

2.3. Test Methods

2.3.1. The Strength of MOCLC. All considered LC mixtures were produced at the optimum moisture content (OMC). The OMC and maximum dry density (MDD) values of the considered LC mixtures were evaluated based on the Chinese standard JTG E51-2009 [35].

A universal testing machine with an accuracy of ±1% was employed to test the strength of MOCLC. First, hardened samples and cubes with a side length of 150 mm were utilized to test the compressive strength and splitting strength of the MOCLC. Second, 12 groups of MOCLC were prepared according to the division criteria in Section 2.1. Accordingly, an average of three specimens was prepared for

Table 4: Chemical compositions of considered FA, DP, and LP.

Oxides	SiO_2	MgO	Al_2O_3	CaO	Fe_2O_3	$CaCO_3$	$MgCO_3$	Na_2O
FA (%)	54.8	0.6	33.1	2.24	4.3	—	—	0.25
DP (%)	0.42	21.05	0.28	0.4	0.16	70.5	3.25	0.08
LP (%)	37.2	1.1	12.5	45.8	1.12	0.03	0.06	0.2

Table 5: Mixing proportions of MOCLC.

No	Magnesium oxide content (%)	Magnesium oxide (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Magnesium chloride (kg/m^3)	Water (kg/m^3)
$MOCLC_1$	3	68	815	1449	31	34
$MOCLC_2$	3.5	77	810	1441	35	37
$MOCLC_3$	4	89	808	1438	37	37
$MOCLC_4$	4.5	98	805	1435	39	39
$MOCLC_5$	5	110	802	1431	45	41

each age. The strength values of different types of MOCLC at each age were then calculated using three groups of parallel test values. Finally, the compressive strength of the MOCLC was determined at the ages of 1, 3, 7, 14, and 28 days. The splitting strength of the MOCLC was determined at 28 days.

2.3.2. Water Resistance of MOCLC. The water resistance of MOCLC was evaluated by the water resistance coefficient [23, 25]. The water resistance coefficient is defined as the ratio of the immersed compressive (splitting) strength to the dry compressive (splitting) strength of the specimen and is calculated using the following formula:

$$K = \frac{f_{\text{imm}}}{f_{\text{dry}}}, \tag{4}$$

where K denotes the water resistance coefficient of MOCLC. f_{imm} and f_{dry} denote the immersion compressive (splitting) strength and dry compressive (splitting) strength of the MOCLC, respectively, for a given period. Evidently, the larger the water resistance coefficient of the specimens, the better the water resistance. The specimens for dry conditioning were placed in a dry conditioning chamber at a room temperature of 20 ± 1°C for 1 day, 3 days, 7 days, 14 days and 28 days, respectively. The specimens were placed in a water tank with a water temperature of 25 ± 3°C for 1 day, 3 days, 7 days, 14 days, and 28 days, respectively. The specimens soaked to the specified age were removed and placed in an oven at 40°C for 24 h to dry [36]. After that, the compression test and splitting test were conducted. In addition, the specimens were tested for water absorption and porosity according to standard ASTM C642-06 [37].

2.3.3. Shrinkage Property of MOCLC. The shrinkage coefficient of the MOCLC was obtained by curing a specimen with a molding size of 100 mm × 100 mm × 400 mm by using a box curing for 7 days at a temperature of 20 ± 1°C and a relative humidity of 60 ± 5%, as specified by Chinese standard JTG E51-2009 [35].

Surface moisture was removed from the test piece, and a vernier caliper was used to measure the datum length before placing the test piece in the shrinkage instrument. The accuracy of the vernier caliper was 0.01 mm. The shrinkage instrument containing the test piece was then placed in a curing box. After curing to the specified age, the test piece was removed, the dial indicator reading $X_{i,j}$ was recorded, and the mass m_i of the standard test piece was weighed. The shrinkage coefficient was calculated using the ratio of shrinkage strain to water loss rate, which was calculated using the following formula:

$$\begin{aligned} \alpha_{di} &= \frac{\varepsilon_i}{w_i}, \\ \varepsilon_i &= \frac{\delta_i}{l}, \\ \delta_i &= \frac{\left(\sum_{j=1}^{4} X_{i,j} - \sum_{j=1}^{4} X_{i+1,j}\right)}{2}, \\ w_i &= \frac{(m_i - m_{i+1})}{m_p}, \end{aligned} \tag{5}$$

where α_{di} corresponds to the shrinkage coefficient of the MOCLC, ε_i represents the shrinkage strain of the MOCLC sample, the value of the dry shrinkage was tested at the ith time, $X_{i,j}$ is the reading of the jth dial indicator at the ith test of the dry shrinkage, l denotes the length of a standard MOCLC sample, w_i is the water loss rate of the test piece, and m_p indicates the constant value for the standard MOCLC sample after drying.

To explore the effect of mineral admixtures on the shrinkage properties of MOCLC, the shrinkage properties of MOCLC were compared by adding FA, DP, and LP. FA and LP were incorporated in a proportion of 25% by a mass of lightly burned magnesia powder in the same proportion. DP replaced 25% of the lightly burned magnesium oxide powder in excess with a mass ratio of 1 : 3.

2.3.4. Fatigue Property of MOCLC. Fatigue is a significant indicator for evaluating the durability of MOCLC [38]. The hardened samples, cuboids of 100 mm × 100 mm × 400 mm, cured at a temperature of 20 ± 2°C and a relative humidity

above 95% for 90 days respectively, were crushed to test the fatigue property, as outlined in the Chinese standard JTG E51-2009 [35]. In the fatigue test, loading was conducted with a continuous sine wave. The loading frequency was set to 10 Hz. In this study, four stress levels were used. Three samples were tested under each stress level. The fatigue equation was calculated using the following formula:

$$\lg N = a + \frac{\sigma}{S}, \qquad \lg N = a + b \lg \sigma, \tag{6}$$

where N denotes the load action time, σ indicates the action load, and S represents the flexural tensile strength of the beam specimens. Moreover, a and b are the regression coefficients.

3. Results and Discussion

3.1. Fresh Properties of MOCLC. Figure 1 shows the effect of the incorporation of cement content on the MDD and OMC values of MOCLC.

As shown in Figure 1, the optimum moisture content (OMC) of $MOCLC_1$, $MOCLC_2$, $MOCLC_3$, $MOCLC_4$, and $MOCLC_5$ is 3.0%, 3.3%, 3.5%, 3.8%, and 4.2%, respectively, and the maximum dry density (MDD) was 2308 kg/m^3, 2313 kg/m^3, 2317 kg/m^3, 2324 kg/m^3, and 2331 kg/m^3, respectively. Besides, the OMC and MDD of the ordinary Portland cement lean concrete (OPCLC) were about 6.5% and 2255 kg/m^3 respectively [39, 40]. Compared with the OPCLC, the MDD value of MOCLC was higher and the OMC value of MOCLC was lower. It was observed that as the percentage of cement content increased from 3% to 5%, both the MDD and OMC of the MOCLC increased slightly. This phenomenon may be explained by the fact that adding cement to a mixture increases the lubricity between particles and the compatibility of the mixture. An increased proportion of the cement slurry can also help plug the pores in the mixture and can enhance its MDD. Owing to the strong water absorption of cement, with an increase in cement content, the OMC also increases.

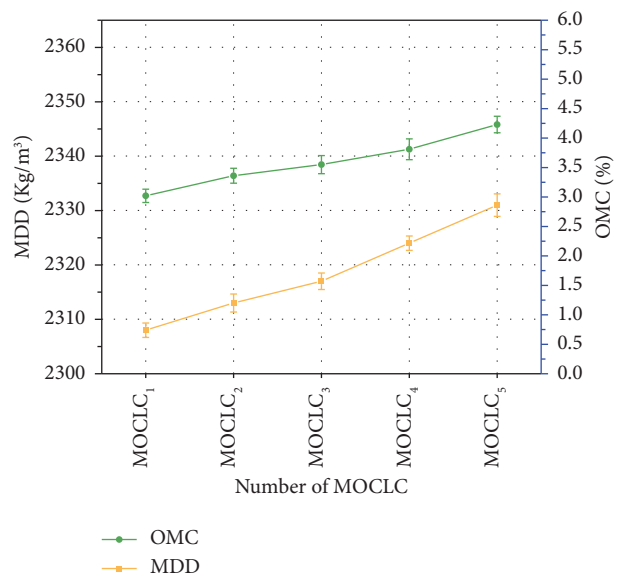

Figure 1: Effect of cement content on fresh properties of MOCLC.

3.2. Mechanical Properties of MOCLC

3.2.1. Compressive Strength. The compressive strength of LC is a physical quantity used to express its compressive bearing capacity of LC per unit area. Figure 2 visually describes the change in the compressive strength of MOCLC with different light-burned magnesia contents and ages.

As shown in Figure 2, the compressive strength of MOCLC increased with the increasing magnesium oxide content and age. This is consistent with Wang Dongxing's conclusion [9]. Wang analyzed the change of specimen strength with MOC content and age by XRD. The peak intensity of phase 5 is observed to increase with the curing time thus revealing that more cementitious products are formed. Besides, the peak intensity of phase 5 enhances with the increase of MOC content, leading to the formation of more phase 5, which can fill in the interparticle pores and cement fine particles together."

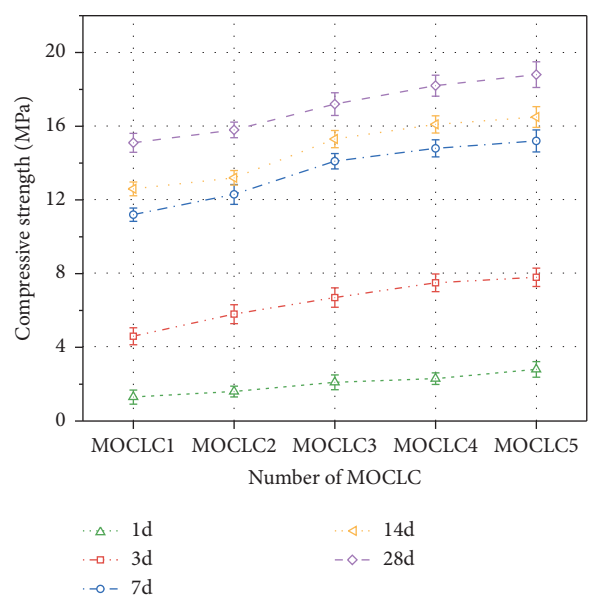

Figure 2: Effect of cement content and age on the compressive strength of MOCLC.

Generally, the compressive strength of MOCLC grew rapidly for the first 7 days and then tended to flatten out. For example, before 7 days, the compressive strength of $MOCLC_3$ increased by approximately 2 MPa/d. However, after seven days, the compressive strength of $MOCLC_3$ only increased by approximately 0.14 MPa/d. Similar patterns in the compressive strength were observed in different contents. Since MOC was used for the preparation of the considered mixes, the rapid increase in the early compressive strength was primarily due to the rapid formation of hydration products, which may have enhanced the chances of strength formation. At 7 days, the compressive strengths of

$MOCLC_3$ were 12 MPa and 7.4 MPa higher than those of $MOCLC_1$ and $MOCLC_2$, respectively. However, compared with $MOCLC_3$, the compressive strengths of $MOCLC_4$ and $MOCLC_5$ did not increase significantly. Obviously, the compressive strength of MOCLC grew the fastest when the magnesium oxide content was 4%.

The effects of mineral admixtures with different types and contents on the compressive strength of MOCLC were investigated using the internal mixing method. The proportion of MgO used in the MOCLC benchmark ratio was 4%. In this study, FA, dolomite powder, and LP were selected to explore the changing trends in the mechanical properties of MOCLC. The content of FA was divided into 10%, 15%, 20%, 25%, and 30%, named as MOCLC-FA_1, MOCLC-FA_2, MOCLC-FA_3, MOCLC-FA_4, and MOCLC-FA_5, respectively, to study the effect of FA on the performance of MOCLC. Similarly, DP and LP follow this naming rule. The test results are shown in Figure 3.

It can be observed from Figure 3 that the compressive strength of MOCLC decreases with an increase in the mineral admixture content. With an increase in mineral admixture content from 10% to 30%, the compressive strength of MOCLC mixed with FA, DP, and LP decreased by 56%, 77%, and 70%, respectively. The influence of FA on the strength of the MOCLC was minimal.

The compressive strength of the MOCLC by the addition of FA is consistent with Wu's study [41]. For instance, compared with the MOCLC-FA_1, the reductions in compressive strength were 9% and 11% for MOCLC-FA_2 and MOCLC-FA_3, respectively. Ultimately, the compressive strength of MOCLC-FA_5 is 16% lower than that of MOCLC-FA_4. It can be observed that the optimum proportion of FA is 25%. These findings suggest that the addition of FA to MOCLC does not promote the development of compressive strength. The reason is that FA breaks the bridge between hydration products and weakens the hydration structure. This phenomenon was also suggested by Wu et al. [41]. Moreover, Gong's study [15] also found that FA disrupts the hydration products of MOC, leading to a decrease in the MOCLC-FA intensity.

Figure 3 shows that the compressive strength of MOCLC is reduced by the addition of DP. The compressive strength of the specimen decreased significantly when the DP addition exceeded 20%. Excess DP resulted in a significant decrease in the compressive strength of MOCLC, which is consistent with the results of Nguyen's study [42]. For instance, compared with MOCLC-DP_1, the reductions in compressive strength were 3% and 14% for MOCLC-DP_2 and MOCLC-DP_3, respectively, whereas the reduction was approximately 39% for both MOCLC-DP_4 and MOCLC-DP_5, respectively. In summary, the optimal content of DP is 20%. The reason is that DP will hinder the contact between lightly burned magnesium powder and magnesium chloride solution, and Liu et al. [43] mentioned a similar theory. Consequently, DP slows the hydration response of the system, resulting in delayed strength development. Moreover, Xu et al. and Yu et al. [44, 45] also suggested that excess DP is equivalent to increasing the proportion of fine aggregates, which will reduce the coarse and fine aggregate ratio and overall strength.

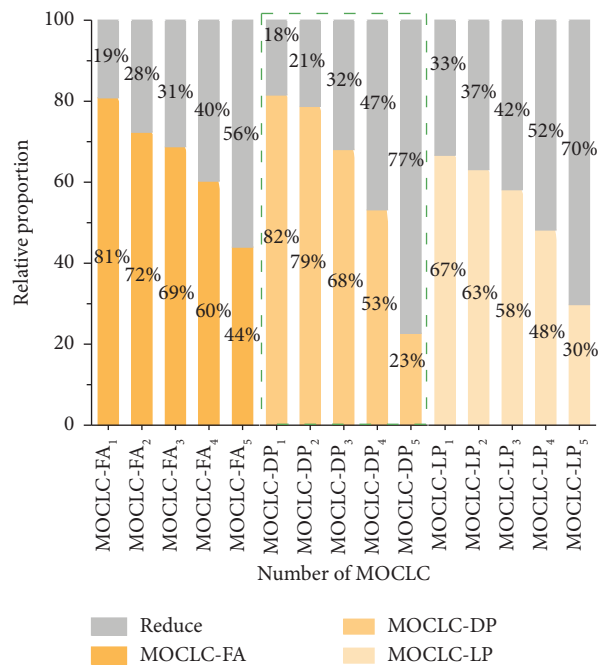

Figure 3: Effect of mineral admixture with different types and contents on compressive strength of MOCLC.

Compared with MOCLC-LP_1, the reductions in compressive strength were 4% and 9% for MOCLC-LP_2 and MOCLC-LP_3, respectively, whereas the reductions were 19% and 37% for MOCLC-LP_4 and MOCLC-LP_5. When the LP content of MOCLC exceeded 20%, the compressive strength of the material rapidly declined. Therefore, the optimum content of LP is 20%. The reason for this phenomenon is that LP is present only as a filler, and Ahmad et al. [46] also pointed out that LP is not involved in hydration reactions and does not contribute to the formation of hydration products.

3.2.2. Splitting Strength. To explore the effect of the magnesium oxide content on the splitting strength of the MOCLC, the splitting strength of the MOCLC was observed at an age of 90 days, as shown in Figure 4.

As shown in Figure 4(a), the variation law of the splitting strength of the MOCLC is similar to that of the compressive strength. The splitting strength increased with an increase in the cement content. The splitting strength of MOCLC rose by approximately 0.53 MPa as the cement content increased from 3% to 5%. Compared with $MOCLC_1$, the increase in splitting strength was 11.8% and 30.1% for $MOCLC_2$ and $MOCLC_3$, respectively, whereas the increase was approximately 35.7% for both $MOCLC_4$ and $MOCLC_5$. Clearly, with 4% MgO, MOCLC exhibited the largest increase in splitting strength. Furthermore, the hydration products of $MOCLC_3$ were generally gel-like and leaf-like crystals with thick architectures. The gel-like crystals can characterize the strength of the MOC paste [47]. Besides, these leaf-like

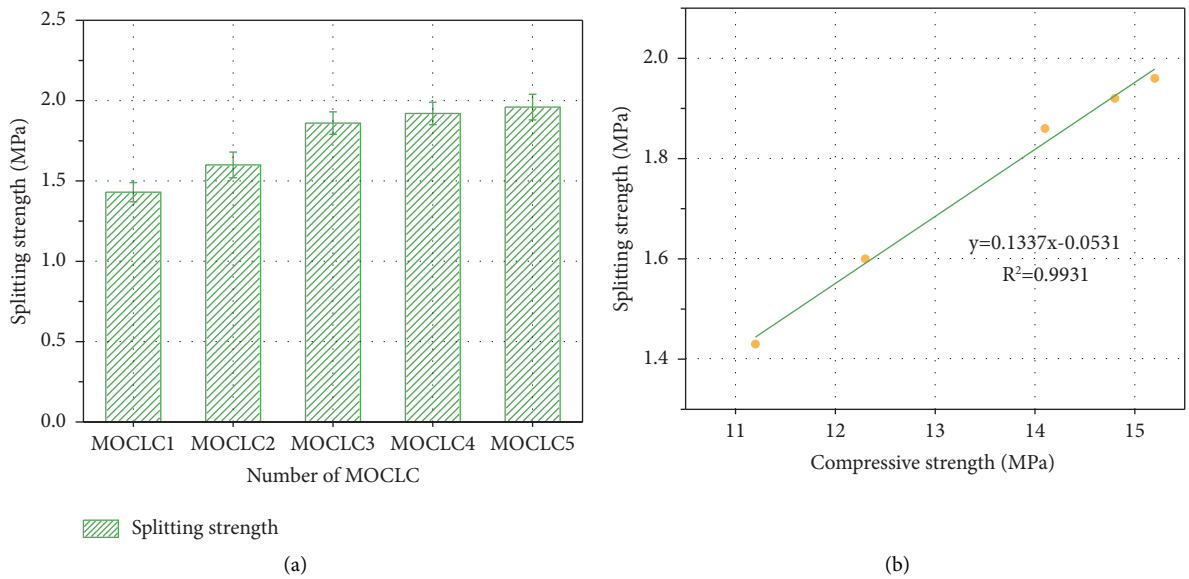

Figure 4: Effect of cement content on MOCLC splitting strength.

crystals can also be referred to as "whiskers," and Wu and Tan's study [48, 49] suggests that these "whiskers" are composed of phase 5 and other substances responsible for the reinforcing strength of the MOC paste. These are the reasons for the rapid increase in the mechanical strength of $MOCLC_3$. Therefore, the optimum content of magnesium oxide should be 4%, which is consistent with the conclusion that an optimum amount of MgO is obtained for the compressive strength.

Figure 4(b) shows the regression analysis of the MOCLC's 7-day compressive strength and 90-day splitting strength of the MOCLC. As shown in Figure 4(b), the compressive strength and splitting strength exhibit a good linear relationship. Therefore, the splitting strength can be calculated indirectly from the compressive strength by using a regression formula. Furthermore, this regression analysis method can be used as a strength test.

Figure 5 shows that the splitting strength of the MOCLC decreases with an increase in the mineral admixture content. This is because the hydration product of MOCLC without mineral admixtures appears as leaf-like crystals, as shown in Figure 6(a). However, the incorporation of mineral admixtures can hinder the formation of these leafy crystals, leading to a reduction in splitting strength. With an increase in mineral admixture content from 10% to 30%, the splitting strength of MOCLC mixed with FA, DP, and LP decreased by 26.3%, 59.6%, and 47.5%, respectively. Therefore, in terms of splitting strength, the effect of FA on the strength of the MOCLC is minimal.

The addition of FA lowered the splitting strength of the MOCLC, as shown in Figure 5. For example, compared with $MOCLC\text{-}FA_1$, the reduction in splitting strength was 12% and 18% for $MOCLC\text{-}FA_2$ and $MOCLC\text{-}FA_3$, respectively, whereas the reduction was approximately 21.5% for both $MOCLC\text{-}FA_4$ and $MOCLC\text{-}FA_5$. Obviously, the incorporation of FA is not conducive to the development of MOCLC splitting strength. In addition, Figure 6(b) shows

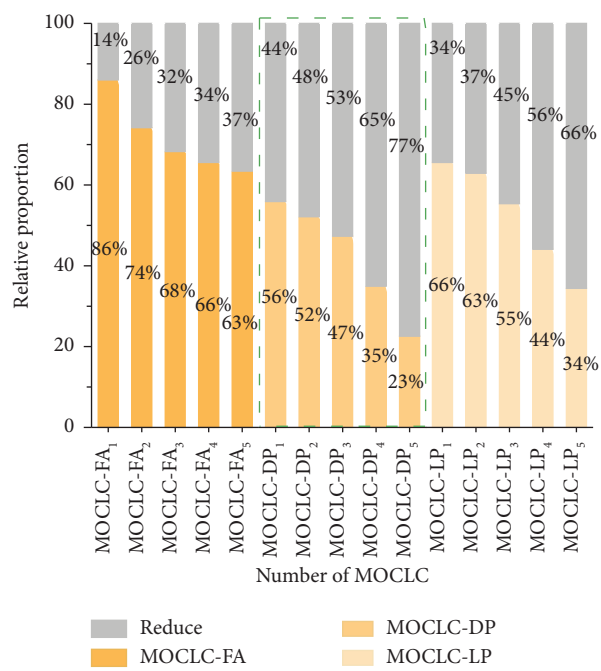

Figure 5: Effect of mineral admixture with different types and contents on splitting strength of MOCLC.

that FA is spherically dispersed in the LC system, which hinders the formation of the flaky gel phase, resulting in hydration products that are mostly short rods. This may be the primary reason for the decrease in the splitting strength of MOCLC. Chau et al. [50] also suggested that FA is spherically distributed in the MOC, which is not conducive to its strength formation.

In Figure 5, compared with the $MOCLC\text{-}DP_1$, the reductions in the splitting strength were 4% and 9% for $MOCLC\text{-}DP_2$ and $MOCLC\text{-}DP_3$, respectively, whereas the

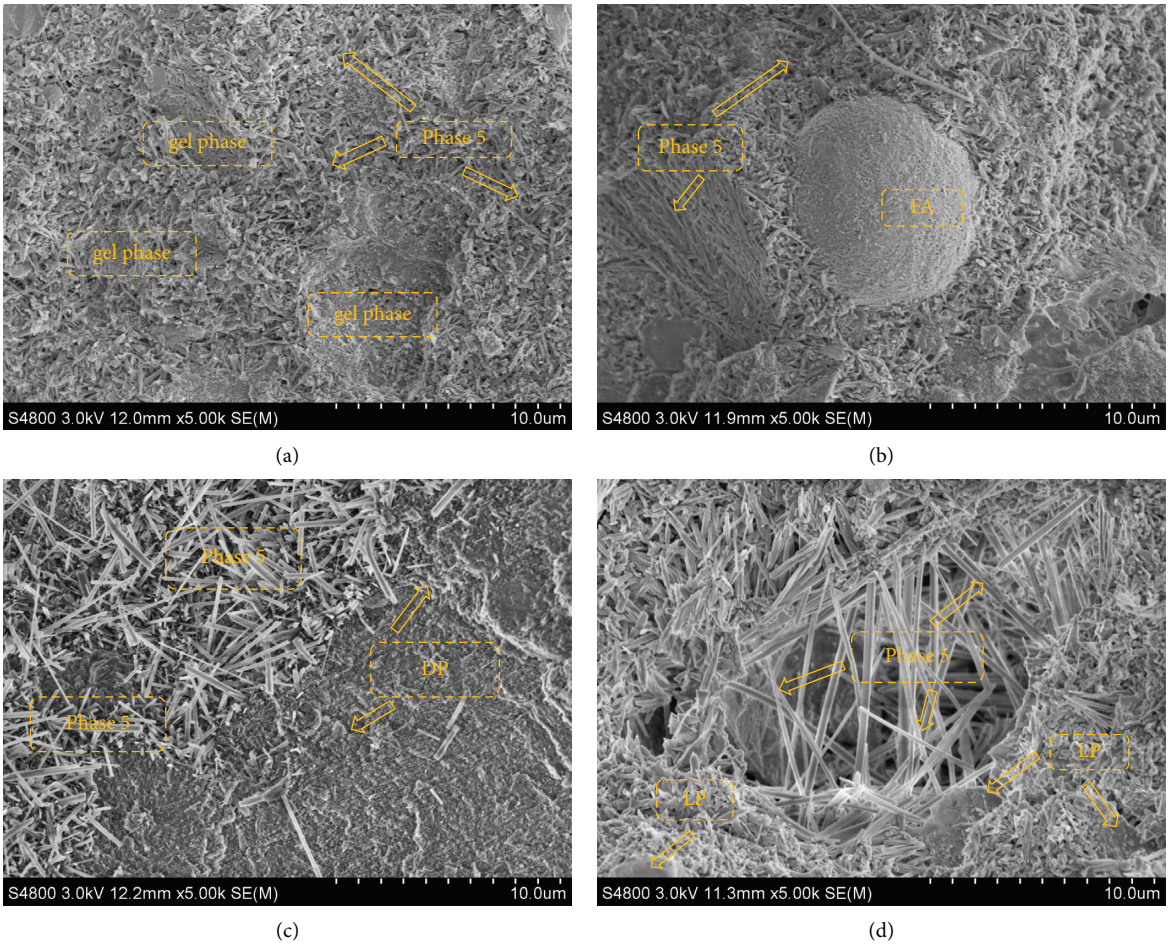

Figure 6: SEM image of MOCLC with mineral admixture. (a) SEM image of MOCLC. (b) SEM image of MOCLC-FA. (c) SEM image of MOCLC-DP. (d) SEM image of MOCLC-LP.

reductions were 21% and 33% for MOCLC-DP_4 and MOCLC-DP_5. Therefore, the addition of DP led to a decrease in the splitting strength of the MOCLC. Figure 6(c) shows the microstructure of the MOCLC-DP. The crystals in the figure primarily exist in the shape of rods. Liu et al. [43] found that the rod-like crystal structure is loose and not conducive to strength formation compared to the flaky gel phase.

Similarly, in Figure 5, compared with MOCLC-LP_1, the reductions in splitting strength were 3% and 11% for MOCLC-LP_2 and MOCLC-LP_3, whereas it was 22% and 32% for MOCLC-LP_4 and MOCLC-LP_5, respectively. Figure 6(d) shows the microstructure of the MOCLC-LP. Apparently, the presence of LP hinders the formation of the gel phase, making the main strength phase appear needle-rod-like. The low reaction state of LP in the cement paste does not provide mechanical strength, which is consistent with Zeng's study [51]. Therefore, LP reduced the strength of the MOCLC.

3.3. Water Resistance of MOCLC

3.3.1. Water Resistance Coefficient. The water resistance coefficient is a physical quantity used to evaluate the water resistance. Figure 7 shows the variation in the waterproof coefficient of the MOCLC under different ages and immersion conditions. In this study, two different immersion conditions of the static and flowing water were set, and the compressive strength and splitting strength were used to calculate the water resistance coefficient of MOCLC, respectively. Specifically, the water resistance coefficient calculated by using the compressive strength for static immersion conditions was denoted as MOCLC-SW-C, and the water resistance coefficient calculated using compressive strength for flowing water immersion conditions was denoted as MOCLC-FW-C. The same was performed for the water resistance coefficient calculated using splitting strength.

As shown in Figure 7, the water resistance coefficient of the MOCLC decreased as the age increased. This phenomenon can be attributed to the fact that phase 5 was unstable in water and hence gets easily decomposed into Mg $(OH)_2$, as shown in Figure 8. Figure 8 shows the XRD spectrum of the specimens at different ages under hydrostatic conditions. From Figure 8, it can be seen that the characteristic peak of phase 5 keeps decreasing and the characteristic peak of Mg $(OH)_2$ increases with the increase

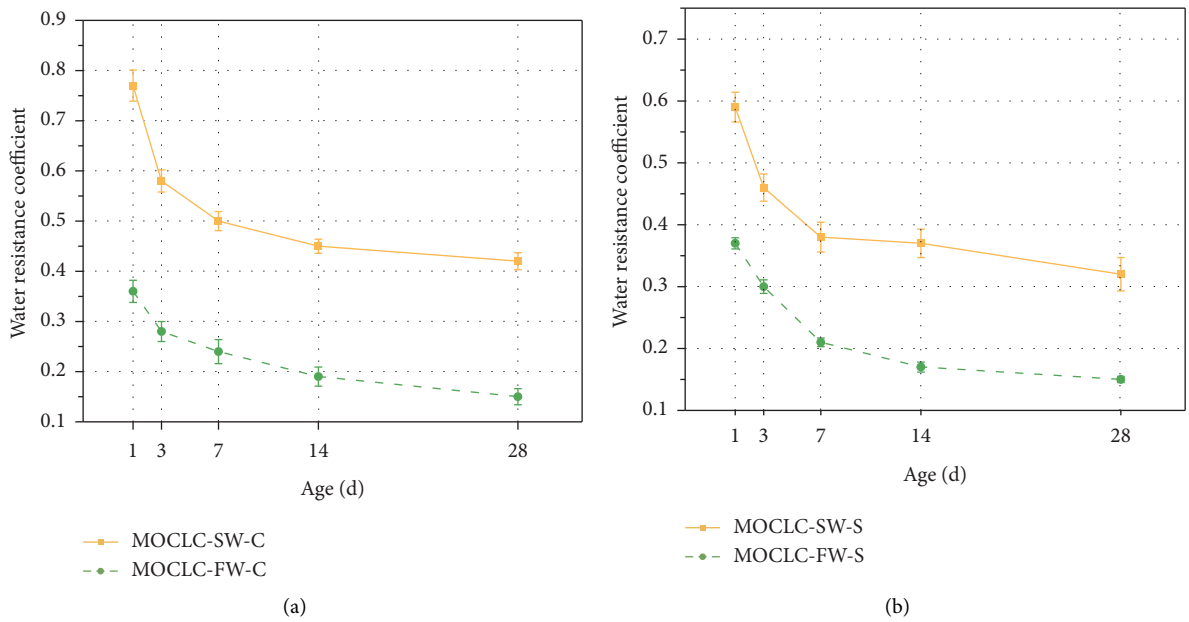

Figure 7: Water resistance coefficient of MOCLC under different water immersion conditions.

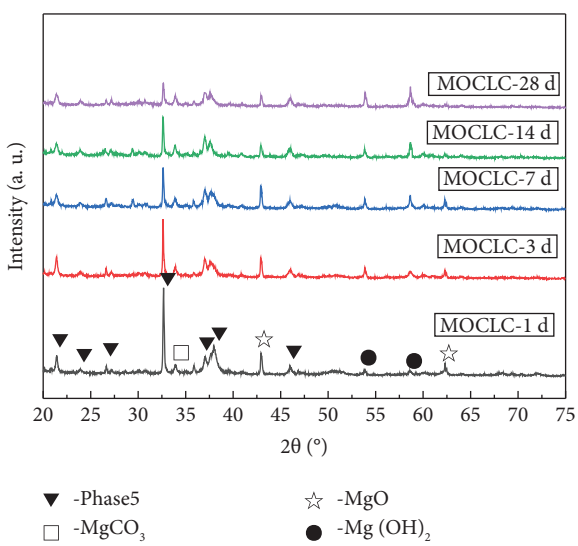

Figure 8: XRD patterns of MOCLC at different immersion ages.

of water immersion age. This is because the hydrolysis product of the phase 5 is mainly Mg $(OH)_2$. The characteristic peak of phase 5 decreased by 65.1% as the age of immersion increased from 1 to 28 days. Phase 5 has a high modulus, which was the main provider of strength for MOCLC, while Mg $(OH)_2$ is a loose layered crystal with a low strength [23]. This indicates that an increase in the number of years of immersion reduces the strength of MOCLC, leading to a decrease in the water resistance coefficient.

In addition, Figure 7(a) shows the change in the water resistance coefficient calculated using the compressive strength. Evidently, at 28 days, the water resistance coefficients of MOCLC-SW-C and MOCLC-FW-C decreased to 0.42 and 0.15, respectively. Obviously, the water resistance coefficient of the MOCLC has a higher strength loss in flowing water than in still water. Figure 7(b) shows the change in the water resistance coefficient calculated using the splitting strength. At 28 days, the water resistance coefficients of MOCLC-SW-S and MOCLC-FW-S decreased to 0.32 and 0.15, respectively. The result is consistent with the conclusions drawn from the compressive strength measurements. Figure 7 shows the lower softening coefficient of the MOCLC specimens in a flowing water environment. It could be chiefly attributed to the differences in ion concentration caused by the transformation of unstable phase 5 into Mg $(OH)_2$ in water. Under flowing water conditions, the ion concentration remained constant, accelerating the dissolution of phase 5.

Figure 9 shows the variation of the water resistance coefficient of MOCLC with the type and content of mineral admixtures. The test conditions included hydrostatic immersion for 7 days. Generally, the water resistance coefficient of MOCLC increased with the addition of mineral admixtures, except for LP.

Figure 9 shows that the water resistance coefficients of MOCLC-FA and MOCLC-DP were higher than those of MOCLC at all test dosages. For instance, when the dosage was 25%, the water resistance coefficient of MOCLC-FA and MOCLC-DP increased by approximately 0.18 and 0.16 compared with MOCLC, respectively. The results reveal that FA and DP had a positive effect on the water resistance coefficient of the MOCLC, which is in agreement with the results of the XRD analysis in Figure 10. In contrast, the results indicated that LP had a negative effect on the water resistance coefficient of the MOCLC, as shown in Figure 10. Compared to MOCLC, the water resistance coefficient of MOCLC-LP was reduced by an average of 30%.

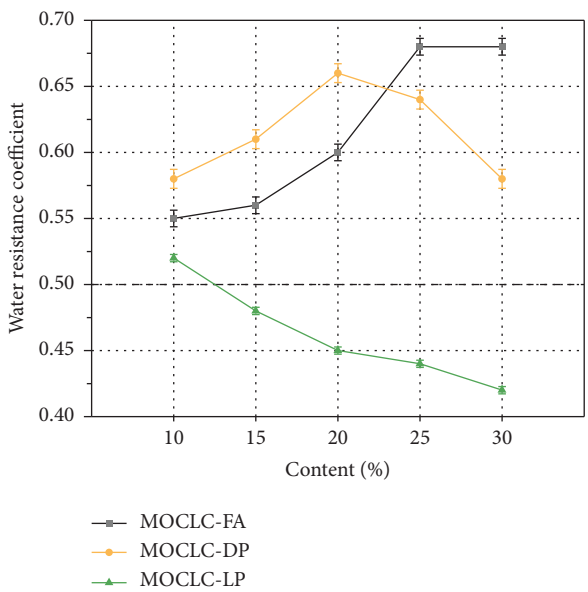

Figure 9: Water resistance coefficient of MOCLC varies with the type and content of mineral admixtures.

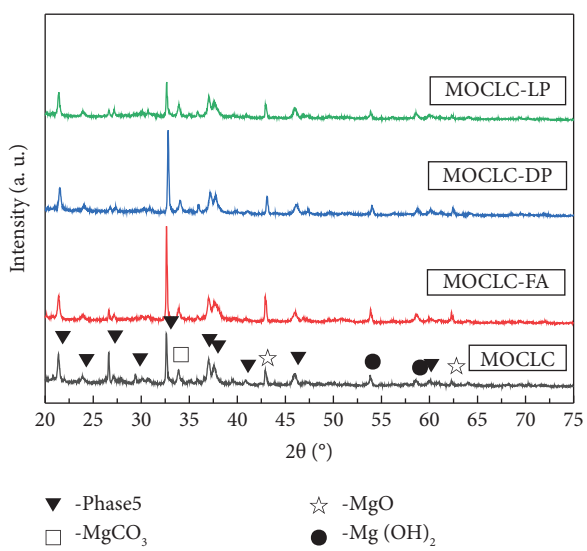

Figure 10: XRD patterns of MOCLC with different mineral admixtures.

Figure 10 shows the XRD spectrum of MOCLC, MOCLC-FA, MOCLC-DP, and MOCLC-LP cured for 7 days. It can be observed from Figure 10 that the MOCLC was comprised of phase 5, Mg $(OH)_2$, Mg CO_3, and MgO. Hydration products of MOC primarily included Mg $(OH)_2$ and phase 5. During water immersion, the inclusion of FA and DP raised the characteristic peaks of phase 5 by 36% and 32%, respectively. In addition, the characteristic peak intensity of MgO increased by 25.1% and 19.7%, respectively. However, the characteristic peak intensity of Mg $(OH)_2$ decreased. Chau et al. [50] found that the reason for this phenomenon is that both the degradation of hydration phases and the formation of Mg $(OH)_2$ were reduced by adding fly ash. Furthermore, this also shows that the addition of FA can reduce the harmful pores of MOC paste and slow down the hydrolysis of the 518 phase. This is consistent with the research study of Guo et al. [36]. Moreover, the study by Averina et al. [52] concluded that DP contributes significantly to the filling of the pores of MOC pastes. Hence, there was an increase in the water resistance coefficient of MOCLC modified by FA and DP.

Apparently, the characteristic peaks of phase 5 appear to diminish with the inclusion of LP in MOCLC, whereas the characteristic peaks of Mg $(OH)_2$ appear to increase slightly. This was principally because the addition of LP reduced the gel material of MOCLC. As the gel material was reduced, the gel phase and crystals in the MOC became more dispersed [53], and the hydrated gel phase was more easily exposed to water because of the inability of the LP to bind the crystal phase together. Therefore, when eroded by water, the gel phase and crystals are more easily hydrolyzed, thus reducing the water resistance of the MOCLC.

3.3.2. Water Absorption and Porosity. The water absorption and porosity of the specimens under different conditions are shown in Figure 11. The water absorption of the specimen under still water conditions was recorded as W-MOCLC-SW, and the porosity of the specimen was recorded as P-MOCLC-SW. Similarly, the water absorption of the specimen under flowing water conditions was recorded as W-MOCLC-FW, and the porosity of the specimen was recorded as P-MOCLC-FW. The water absorption of MOCLC doped with fly ash was recorded as W-MOCLC-FA, and the porosity was recorded as P-MOCLC-FA. The specimens doped with dolomite powder and limestone powder were marked in the same way as mentioned above.

Figure 11(a) shows that water absorption and porosity increase with the increasing age of immersion. This was in line with the results of Wang et al. [7]. The water absorption of the specimens immersed for 7 days and immersed for 28 days in a static water environment increased by 7.1% and 8.2%, respectively. The water absorption of the specimens immersed for 7 days and 28 days increased by 11.4% and 14.2%, respectively, in the flowing water environment. Obviously, the water absorption rate of the specimen in the flowing water environment increased more dramatically. The water absorption rate of the specimens grew rapidly in the first 7 days of immersion. Wang et al. [7] suggested that this is because most of the free water is absorbed and fills the pore space of the cured sample within 2 days, while longer immersion times contribute less to the overall amount of absorbed water. The porosity of the specimens immersed for 7 and 28 days in a static water environment increased by 9.2% and 10.6%, respectively. In the flowing water environment, the water absorption of the specimens immersed for 7 and 28 days increased by 11.5% and 13.8%, respectively. The variation pattern of porosity in Figure 11(a) also confirms Wang's view [7].

Figure 11(b) shows the variation of water absorption and porosity for different contents of MOCLC-FA, MOCLC-DP,

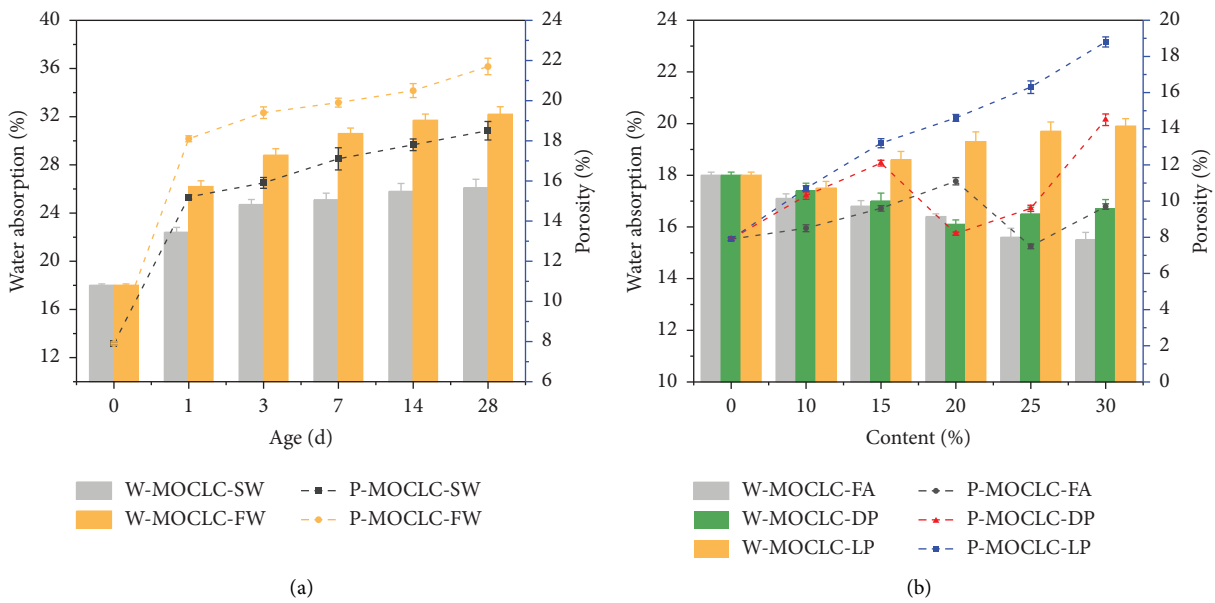

Figure 11: Water absorption and porosity of MOCLC.

and MOCLC-LP. The addition of FA and DP reduced the water absorption of the specimens by 2.5% and 1.35, respectively, compared to the reference specimens. However, the addition of LP increased the water absorption of the specimens by 2% and reduced the water resistance of the specimens. This is consistent with the conclusion of the water resistance coefficient in Section 3.3.1. Besides, after doping with FA and DP, the pores of the specimens increased first, then fluctuated, and finally tended to rise again. Guo et al. [36] explained the reason for this phenomenon. This is because the incorporation of FA and DP, while reducing the harmful macropores of the MOC paste, increases the small internal pores with a pore size of less than 50 nm. The increase in small pores was greater than the decrease in large pores, which led to an increase in the overall porosity. When the content of FA and DP is 25% and 20%, respectively, the filling effect on the MOC paste is the best, which densifies the MOC paste, so the porosity curve fluctuates. However, the excess admixture destroys the internal structure of the MOC paste, which leads to another increase in the porosity curve. This was also illustrated by Chau et al. [50]. The doping of LP increased the porosity of the specimens by about 10%, indicating that LP had a negative effect on the water resistance performance of MOCLC. This is in agreement with the study of Mostofinejad et al. [54].

3.4. Shrinkage Properties of MOCLC. Studies have demonstrated that the deterioration in the mechanical properties and durability of LC structures is primarily caused by shrinkage cracking. Furthermore, shrinkage affects MOCLC far more than it affects ordinary Portland cement lean concrete. Figure 12 shows the differences between the shrinkage strains of the MOCLC under the base ratio and mineral admixture conditions. Owing to the rapid hydration

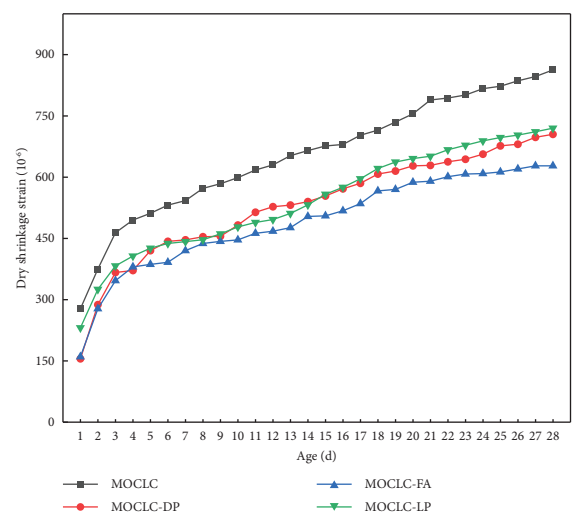

Figure 12: Relationship between dry shrinkage strain and time of different admixtures.

of MOC, shrinkage testing was performed in this trial starting on the first day of molding.

Figure 12 shows that the dry shrinkage strain of the MOCLC increased to different degrees with age. According to previous studies, the evaporation of water creates a large number of capillary pores inside the MOCLC [55]. Generally, the dry shrinkage strains of MOCLC-FA, MOCLC-DP, and MOCLC-LP were lower than that of the MOCLC. The dry shrinkage strains of MOCLC-FA, MOCLC-DP, and MOCLC-LP decreased approximately by 27.2%, 18.3%, and 16.5%, respectively. The results exhibited that FA, DP, and LP positively affected the shrinkage performance of the MOCLC. The reasons cited for this declined behaviour were the addition of FA, DP, and LP which reduced the amount of cement in the voids between aggregates. This led to the lesser

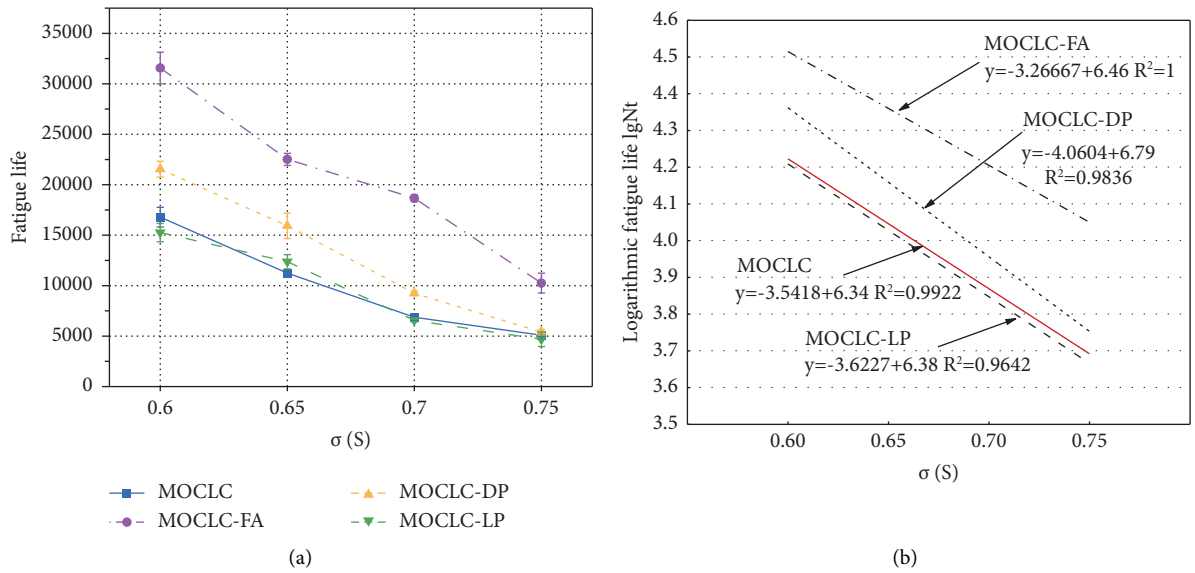

Figure 13: Comparison of MOCLC fatigue life under different mineral admixtures.

drying shrinkage [1]. During the drying process, MOCLC samples lost their quality due to the gradual loss of free water and crystal water [23]. With the extension of drying time, the dehydration process can be divided into two steps. Step 1: MOCLC sample gradually loses free water. Step 2: phase 5 in the MOCLC sample loses crystal water. Phase 5 is converted from 5Mg $(OH)_2 \cdot MgCl_2 \cdot 8H_2O$ to 5Mg $(OH)_2 \cdot MgCl_2$. The porous and the loose structure of FA has a strong water absorption capacity, which can accelerate the drying of cement interior and can reduce the loss of free water and crystal water [36]. In addition, FA is spherical, with low hydration reaction [56], and can also play a filling role. Therefore, the incorporation of FA reduced the shrinkage strain of the MOCLC. Additionally, DP was finer than ordinary mineral admixtures [57], which could better fill the internal pores of the MOCLC and can improve the pore structure. Additionally, $CaCO_3$ in the DP reacted with calcium aluminate hydrate to form monocarbon aluminate hydrate or tricarbon aluminate hydrate, which could compensate for its volume shrinkage. Additionally, as an inert material, LP is mostly used as a filler for MOCLC to disperse the cementitious phase, thereby reducing its shrinkage strain.

As shown in Figure 12, before 3 days, the shrinkage strain of the MOCLC increased rapidly and flattened after three days. The variation law of the shrinkage strain of the MOCLC with the mineral admixture was the same as that of the standard ratio. On an average, MOCLC-FA exhibited the largest reduction in shrinkage strain of approximately 25% compared to the standard ratio. The reduction in shrinkage strain of MOCLC-DP and MOCLC-LP was similar, approximately 20%. Therefore, adding 25% FA had the best effect in improving the shrinkage properties of MOCLC.

3.5. Fatigue Properties of MOCLC. Figure 13(a) shows the fatigue life of the MOCLC at different stress levels. The logarithmic average fatigue life $\lg N_t$ is taken as the ordinate and the stress level σ/S as the abscissa to perform the linear fitting and regression, as shown in Figure 13(b). Considering the abovementioned shrinkage and mechanical properties of the MOCLC, the stress ratios of the four fatigue tests were considered as 0.6, 0.65, 0.7, and 0.75, respectively.

Figure 13 shows that the increase in the stress level decreased the fatigue life of MOCLC. The fatigue life of MOCLC-FA, MOCLC-DP, and MOCLC-LP increased by 88.0%, 28.4%, and −9.1%, respectively, according to the fitting equation shown in Figure 13. It can be observed that the fatigue curves of MOCLC-FA and MOCLC-DP were located above the fatigue curve of MOCLC, while the fatigue curve of MOCLC-FA was much higher than that of MOCLC-DP. More specifically, the fatigue curves of MOCLC-LP and MOCLC were roughly identical. This implied that the anti-fatigue performance of MOCLC-FA was the best, followed by MOCLC-DP, and MOCLC and MOCLC-LP which were the lowest. Therefore, at the same stress level, MOCLC-FA could bear the most load times, followed by MOCLC-DP, MOCLC, and MOCLC-LP.

Regarding the fatigue curve, the slope of the fatigue curve of MOCLC-FA was the smallest, and the slope of the fatigue curve of MOCLC-DP was the largest. The research of Li et al. and Sun et al. [58, 59] shows that the sensitivity of fatigue life to stress level is reflected by the slope of the fatigue curve. Obviously, the change in stress level had the least effect on the fatigue life of MOCLC-FA. Furthermore, MOCLC-DP exhibited the highest fatigue sensitivity. In summary, FA doping had the best effect on enhancing the fatigue properties of the MOCLC.

4. Conclusions

A comprehensive investigation of the mechanics and durability of MOCLC was conducted using a series of physical mechanical, durability, and microstructural tests. Based on

the obtained data, the following conclusions were drawn regarding the characteristics of the MOCLC:

(1) The addition of MOC improves the compaction characteristics of lean concrete. As the content of light-burned magnesia increased from 3% to 5%, the MDD and OMC of MOCLC increased by 0.96% and 40.1%, respectively.

(2) The compressive and splitting strengths of MOCLC were reduced by the addition of FA, DP and LP, however, its durability was improved. The optimal contents of FA, DP, and LP were 25%, 20% and 20%, respectively.

(3) FA and DP improved the water resistance of MOCLC, but LP was detrimental to the water resistance of MOCLC. The water resistance coefficients of MOCLC-FA and MOCLC-DP were increased by 0.18 and 0.16, respectively, relative to the control sample. And the water resistance coefficient of MOCLC-LP was reduced by an average of 30%.

(4) The shrinkage resistance of MOCLC composites is in the following order: MOCLC-FA > MOCLC-DP > MOCLC-LP > MOCLC. MOCLC-FA has better fatigue properties than DP and LP.

(5) The water resistance, shrinkage, and fatigue properties of MOCLC with a FA content of 25% were better than those of MOCLC with DP and LP.

Data Availability

The data supporting the current study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] R. K. Khyaliya, K. S. A. Kabeer, and A. K. Vyas, "Evaluation of strength and durability of lean mortar mixes containing marble waste," *Construction and Building Materials*, vol. 147, pp. 598–607, 2017.

[2] S. Lijun and W. Xinwu, "Analysis of load stress for asphalt pavement of lean concrete base," *Physics Procedia*, vol. 24, pp. 404–411, 2012.

[3] M. Singh, R. S. Chhabra, and A. Adhikari, "Feasibility study on use of washed-reclaimed asphalt as a partial replacement of natural aggregate in dry-lean concrete as base course for rigid pavement[J]," *Journal of Materials in Civil Engineering*, vol. 32, no. 9, Article ID 04020266, 2020.

[4] S. Reddy Kasu and S. Patel, "Field experiments and numerical analysis of curling behavior of cast-in-situ short paneled concrete pavement on lean concrete base[J]," *International Journal of Pavement Engineering*, pp. 1–14, 2021.

[5] S. R. Kasu, J. Tangudu, A. K. Chandrappa, and M. Reddy, "Influence of stiffness of dry lean concrete base on load stresses in the plain cement concrete slab of concrete pavements," *Road Materials and Pavement Design*, vol. 23, no. 8, pp. 1942–1955, 2021.

[6] A. Singh, R. Kumar, and P. Goel, "Factors influencing strength of magnesium oxychloride cement," *Construction and Building Materials*, vol. 303, Article ID 124571, 2021.

[7] D. Wang, X. Gao, X. Liu, and G. Zeng, "Strength, durability and microstructure of granulated blast furnace slag-modified magnesium oxychloride cement solidified waste sludge," *Journal of Cleaner Production*, vol. 292, Article ID 126072, 2021.

[8] Q. Ye, Y. Han, T. Liu et al., "Magnesium oxychloride cement reinforced via D-gluconic acid sodium salt for slow-curing, with enhanced compressive strength and water resistance," *Construction and Building Materials*, vol. 280, Article ID 122487, 2021.

[9] D. Wang, S. Di, X. Gao, R. Wang, and Z. Chen, "Strength properties and associated mechanisms of magnesium oxychloride cement-solidified urban river sludge," *Construction and Building Materials*, vol. 250, Article ID 118933, 2020.

[10] Q. Ye, Y. Han, S. Zhang et al., "Bioinspired and biomineralized magnesium oxychloride cement with enhanced compressive strength and water resistance," *Journal of Hazardous Materials*, vol. 383, Article ID 121099, 2020.

[11] D. H. Deng and C. M. Zhang, "The formation mechanism of the hydrate phases in magnesium oxychloride cement," *Cement and Concrete Research*, vol. 29, no. 9, pp. 1365–1371, 1999.

[12] R. M. Andrew, "Global CO2 emissions from cement production[J]," *Earth System Science Data*, vol. 10, no. 1, pp. 1–52, 2018.

[13] H. Qiao, Q. Cheng, and W. Jinlei, "The application review of magnesium oxychloride cement[J]," *Journal of Chemical and Pharmaceutical Research*, vol. 6, no. 5, pp. 180–185, 2014.

[14] H. Bilinski, B. Matkovic, C. Mazuravic, and T. A. Zunic, "The formation of magnesium oxychloride phases in the system of MgO-MgCl2-H2O and NaOH-MgCl2-H2O," *Journal of the American Ceramic Society*, vol. 67, no. 4, pp. 266–269, 1984.

[15] W. Gong, N. Wang, and N. Zhang, "Effect of fly ash and metakaolin on the macroscopic and microscopic characterizations of magnesium oxychloride cement," *Construction and Building Materials*, vol. 267, no. 1, Article ID 120957, 2021.

[16] D. Menetrier-Sorrentino, P. Barret, and S. Saquat, "Investigation in the system mgo-mgcl2-h2o and hydration of sorel cement," in *Proceedings of the 8th ICCC*, pp. 339–343, Rio de Janeiro, Brazil, September 1986.

[17] B. Matkovic, S. Popovic, and V. Rogic, "Reaction products in magnesium oxychloride cement pastes system MgO-MgCl2-H2O," *[J]. Chemischer Informationsdienst*, vol. 9, no. 17, pp. 504–507, 1978.

[18] J. M. Dong, H. F. Yu, and M. J. Wang, "Influence of fly ash on magnesium oxychloride cement deformation," *Materials Science Forum*, vol. 817, pp. 252–256, 2015.

[19] A. Jiříčková, M. Lojka, A. M. Lauermannová et al., "Synthesis, structure, and thermal stability of magnesium oxychloride 5 Mg $(OH)_2 \cdot MgCl_2 \cdot 8H_2O$[J]," *Applied Sciences*, vol. 10, p. 1683, 2020.

[20] M. Lojka, O. Jankovský, A. Jiříčková et al., "Thermal stability and kinetics of formation of magnesium oxychloride phase 3 Mg $(OH)_2 \cdot MgCl_2 \cdot 8H_2O$[J]," *Materials*, vol. 13, no. 3, p. 767, 2020.

[21] P. Wang, H. Qiao, Y. Zhang, Y. Li, Q. Feng, and K. Chen, "Meso-damage evolution analysis of magnesium oxychloride cement concrete based on X-CT and grey-level co-occurrence matrix," *Construction and Building Materials*, vol. 255, Article ID 119373, 2020.

[22] P. Wang, H. Qiao, Y. Li, K. Chen, Q. Feng, and T. Nian, "Durability of organic coated reinforced magnesium oxychloride cement concrete," *Structural Concrete*, vol. 22, no. 5, pp. 2595–2610, 2021.

[23] Q. Huang, W. Zheng, X. Xiao, J. Dong, J. Wen, and C. Chang, "Effects of fly ash, phosphoric acid, and nano-silica on the properties of magnesium oxychloride cement," *Ceramics International*, vol. 47, no. 24, pp. 34341–34351, 2021.

[24] C. Chang, J. Dong, X. Xiao et al., "Long-term mechanical properties and micro mechanism of magnesium oxychloride cement concrete," *Advances in Cement Research*, vol. 32, no. 8, pp. 371–378, 2020.

[25] Y. Hao and Y. Li, "Study on preparation and properties of modified magnesium oxychloride cement foam concrete," *Construction and Building Materials*, vol. 282, Article ID 122708, 2021.

[26] W. Gong, N. Wang, N. Zhang, W. Han, and H. Qiao, "Water resistance and a comprehensive evaluation model of magnesium oxychloride cement concrete based on Taguchi and entropy weight method," *Construction and Building Materials*, vol. 260, Article ID 119817, 2020.

[27] M. Záleská, M. Pavlíková, and Z. Pavlík, "Structural, mechanical and thermal properties of lightweight magnesium oxychloride cement concrete," *AIP Conference Proceedings*, vol. 2170, no. 1, 2019.

[28] H. Qiao, W. Gong, Y. Shi, M. E. Wanjiru, and J. Dong, "Experimental study on magnesium oxychloride cement concrete," *Emerging Materials Research*, vol. 5, no. 2, pp. 248–255, 2016.

[29] P. Wang, H. Qiao, H. Cao, Q. Feng, and K. Chen, "Durability analysis of magnesium oxychloride coated reinforced concrete under the combined effect of carbonization and water loss," *Emerging Materials Research*, vol. 9, no. 2, pp. 1–13, 2020.

[30] T. Huang, Q. Yuan, and D. Deng, "The role of phosphoric acid in improving the strength of magnesium oxychloride cement pastes with large molar ratios of H2O/MgCl2," *Cement and Concrete Composites*, vol. 97, pp. 379–386, 2019.

[31] Y. Wang, L. Wei, J. Yu, and K. Yu, "Mechanical properties of high ductile magnesium oxychloride cement-based composites after water soaking," *Cement and Concrete Composites*, vol. 97, pp. 248–258, 2019.

[32] Gb/T 14685-2011, *Pebble and Gravel for Construction*, Ministry of Transport, Beijing, China, 2011.

[33] Jgj 63-2006, *Standard for Water for Concrete*, Ministry of Construction, Beijing, China, 2006.

[34] Jtg 3420-2020, *Test Specification for Cement and Cement Concrete of Highway Engineering*, Ministry of Construction, Beijing, China, 2020.

[35] J. T. G. E51-2009, *Test Specification for Inorganic Binder Stabilized Materials of Highway Engineering*, Ministry of Construction, Beijing, China, 2009.

[36] Y. Guo, Y. X. Zhang, K. Soe, R. Wuhrer, W. D. Hutchison, and H. Timmers, "Development of magnesium oxychloride cement with enhanced water resistance by adding silica fume and hybrid fly ash-silica fume," *Journal of Cleaner Production*, vol. 313, Article ID 127682, 2021.

[37] Astm C 642, *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*, Annual Book of ASTM Standards, West Conshohocken, PA, USA, 2006.

[38] J. A. Sainz-Aja, I. A. Carrascal, J. A. Polanco, and C. Thomas, "Effect of temperature on fatigue behaviour of self-compacting recycled aggregate concrete," *Cement and Concrete Composites*, vol. 125, Article ID 104309, 2022.

[39] S. Singh, G. Ransinchung Rn, and K. Monu, "Sustainable lean concrete mixes containing wastes originating from roads and industries," *Construction and Building Materials*, vol. 209, pp. 619–630, 2019.

[40] S. Singh, G. D. R. N. Ransinchung, K. Monu, and P. Kumar, "Laboratory investigation of RAP aggregates for dry lean concrete mixes," *Construction and Building Materials*, vol. 166, no. 30, pp. 808–816, 2018.

[41] J. Wu, H. Chen, and B. Guan, "Effect of fly ash on rheological properties of magnesium oxychloride cement[J]," *Journal of Materials in Civil Engineering*, vol. 31, no. 3, Article ID 04018405, 2019.

[42] H. Nguyen, "Enhancement of engineering properties of slag-cement based self-compacting mortar with dolomite powder," *Journal of Building Engineering*, vol. 24, Article ID 100738, 2019.

[43] Z. Liu, S. Wang, J. Huang, Z. Wei, B. Guan, and J. Fang, "Experimental investigation on the properties and microstructure of magnesium oxychloride cement prepared with caustic magnesite and dolomite," *Construction and Building Materials*, vol. 85, pp. 247–255, 2015.

[44] J. Xu, J. Chen, D. Lu, Z. Xu, and R. Hooton, "Effect of dolomite powder on the hydration and properties of calcium sulfoaluminate cements with different gypsum contents," *Construction and Building Materials*, vol. 225, pp. 302–310, 2019.

[45] J. Yu, J. Qian, F. Wang et al., "Study of using dolomite ores as raw materials to produce magnesium phosphate cement," *Construction and Building Materials*, vol. 253, Article ID 119147, 2020.

[46] S. Ahmad, A. Bahraq, and A. Shaqraa, "Effects of key factors on the compressive strength of metakaolin and limestone powder-based alkali-activated concrete mixtures: an experimental and statistical study," *Case Studies in Construction Materials*, vol. 16, p. e915, 2022.

[47] B. Guan, H. Tian, D. Ding, J. Wu, and R. Xiong, "Effect of citric acid on the time-dependent rheological properties of magnesium oxychloride cement," *Journal of Materials in Civil Engineering*, vol. 30, no. 11, Article ID 04018275, 2018.

[48] J. Wu, B. Guan, H. Chen, H. Tian, J. Liu, and R. Xiong, "Effects of polycarboxylate superplasticiser on the early hydration properties of magnesium oxychloride cement," *Construction and Building Materials*, vol. 259, Article ID 119862, 2020.

[49] Y. Tan, Y. Liu, Z. Zhao, J. Z. Paxton, and L. M. Grover, "Synthesis and*in vitro*degradation of a novel magnesium oxychloride cement: synthesis and *In Vitro* Degradation of

a Novel MOC," *Journal of Biomedical Materials Research Part A*, vol. 103, no. 1, pp. 194–202, 2015.

[50] C. K. Chau, J. Chan, and Z. Li, "Influences of fly ash on magnesium oxychloride mortar," *Cement and Concrete Composites*, vol. 31, no. 4, pp. 250–254, 2009.

[51] H. Zeng, Y. Li, J. Zhang, P. Chong, and K. Zhang, "Effect of limestone powder and fly ash on the pH evolution coefficient of concrete in a sulfate-freeze–thaw environment," *Journal of Materials Research and Technology*, vol. 16, pp. 1889–1903, 2022.

[52] G. F. Averina, T. N. Chernykh, and K. V. Shuldyakov, "Hardening stowing mixture based on technological dolomite," *Procedia Engineering*, vol. 206, pp. 790–794, 2017.

[53] C. Ma, G. Chen, J. Shi, H. Zhou, W. Ren, and Y. Du, "Improvement mechanism of water resistance and volume stability of magnesium oxychloride cement: a comparison study on the influences of various gypsum," *Science of the Total Environment*, vol. 829, Article ID 154546, 2022.

[54] D. Mostofinejad, M. Khademolmomenin, and B. Tayebani, "Evaluating durability parameters of concrete containing limestone powder and slag under bacterial remediation," *Journal of Building Engineering*, vol. 40, Article ID 102312, 2021.

[55] W. Xu, Z. Song, M. Guo, L. Jiang, and H. Chu, "Improvement in water resistance of magnesium oxychloride cement via incorporation of dredged sediment," *Journal of Cleaner Production*, vol. 356, Article ID 131830, 2022.

[56] Y. Li, H. Yu, L. Zheng, J. Wen, C. Wu, and Y. Tan, "Compressive strength of fly ash magnesium oxychloride cement containing granite wastes," *Construction and Building Materials*, vol. 38, pp. 1–7, 2013.

[57] H. A. Nguyen, T. P. Chang, J. Y. Shih, and H. Suryadi Djayaprabha, "Enhancement of low-cement self-compacting concrete with dolomite powder," *Construction and Building Materials*, vol. 161, pp. 539–546, 2018.

[58] L. Li, Q. Zheng, X. Wang, B. Han, and J. Ou, "Modifying fatigue performance of reactive powder concrete through adding pozzolanic nanofillers," *International Journal of Fatigue*, vol. 156, Article ID 106681, 2022.

[59] X. Sun, Y. Tian, W. Yin, and H. Wang, "Effect of free water on fatigue performance of concrete subjected to compressive cyclic load," *Construction and Building Materials*, vol. 318, Article ID 125995, 2022.