IJEIT
The International Journal of Engineering and Information Technology
journal homepage:www.ijeit.misuratau.edu.ly
MISURATA UNIVERSITY

Durability-Related Transport Properties of Limestone Calcined Clay Cement Mortars

Saad Alferjani
Department of Civil Engineering, Omar Al Mukhtar University, El Beida, Libya
saad.alferjani@omu.edu.ly

Farhat Abubaker
Department of Civil Engineering, Omar Al Mukhtar University, El Beida, Libya
farhat.abubaker@omu.edu.ly

Abstract— **This study investigates the effect of utilizing a combination of limestone and calcined clay as cement replacement on the transport properties that indirectly define the behavior of the matrix throughout its service life, such as total porosity, water absorption due to capillary action, water permeability penetration, chlorine diffusion, and carbonation depth. Mortars were made of blends with different levels of cement replacement (%15, %30, %45) by a substitution ratio of 2:1 (calcined clay: limestone), with adjusted gypsum content in each system composition. Furthermore, the influence of kaolinite content in clays on transport properties was also investigated. Based on the results, all LC^3 blends exhibited a significant improvement in terms of total porosity, capillary water absorption, water penetration resistance, and chloride diffusion compared to OPC mortars. Moreover, the higher the replacement level of cement, the higher the resistance to movement or transport of ion species through the mortars. The improvement in the transport properties for LC^3 blends can be attributed to its enhanced porosity refinement as well as the enhanced chloride binding capacity. In contrast, a slight improvement in the transport properties was observed with increasing the kaolinite content of the calcined clays. This result indicates that utilizing low-grade calcined clay has no significant effect on the transport properties. The carbonation resistance of the LC^3 blends was lower as compared to OPC. Furthermore, increasing the cement substitution rate resulted in a progressive decrease in carbonation resistance. Overall, an increase in cover depth would be required to achieve a similar service life in terms of carbonation as that of the OPC.**

Index Terms: **LC^3, Calcined clay, Limestone, water resistance, chloride diffusion**

I. INTRODUCTION

The recent societal shift toward sustainable consumption and growth applied to housing and civil infrastructure systems, necessitates that construction materials be designed and used with the utmost consideration to their durability and long-term performance [1]. Durability remains one of the most significant properties of concrete, specifically for structures that are exposed to extreme environments or severe conditions [1-3]. Improvements in concrete's durability performance have been widely accepted by the community as a means of reducing an infrastructure's life-cycle cost, especially in terms of maintenance during its service life [4]. The durability of concrete structures is significantly affected by transport properties such as permeation, diffusion, sorption, and absorption, which allow harmful agents such as water, CO_2, chloride, etc. to penetrate the bulk of the concrete and cause deterioration [1-4].

In recent years, many researchers have established that, in addition to lowering costs and mitigating the environmental issues surrounding cement manufacture, the use of supplementary cementitious materials (SCMs) such as fly ash, blast furnace slag or silica fume enhance the durability of cement binders, largely by reinforcing resistance to fluid transport, and thus improves performance. [5, 6]. These effects are primarily due to the formation of secondary hydration products during the pozzolanic reaction and the resulting alteration of the pore system, in which decreased connectivity raises network complexity and decreases permeability [3, 6, 7]. The growing worldwide demand for cement, however, and the declining availability of the aforementioned SCMs has driven the pursuit of alternative mineral additions [8]. In such a situation, the use of metakaolin in combination with limestone in OPC-based systems is reported to obtain increased substitution levels without impacting concrete characteristics [9, 10]. When limestone and metakaolin are combined, in addition to the pozzolanic reaction of metakaolin and limestone reaction with C_3A, there is the synergetic effect between alumina in calcined clay and limestone producing carbo-aluminate phases. Mono-carbo-aluminate hydrate are formed and fill the pore spaces which will increase the strength [9, 11, 12]. The stoichiometric formation of mono-carboaluminate hydrate (an AFm phase) is by reaction of one mole of metakaolin (MK) with one mole of calcium carbonate CaCO3 (LS) in the presence of water and calcium hydroxide CH to give 1 mol of monocarboaluminate. This corresponds to an addition with a weight ratio of 2:1 MK:LS [9]. This ternary blend of limestone, calcined clay, and clinker is known as LC^3, and it is on its way to proving its potential in the cement industry by solving the twin issues of CO_2 emissions and natural resource conservation. However, the use of this

---

Received 5 Oct, 2021; revised 6 Dec, 2021; accepted 16 Dec, 2021.

Table 1: Chemical composition and Physical properties of the materials

Chemical composition %	**Cement**	**Limestone**	**MKA**	**MKB**	**MKC**
CaO	63.09	54.53	0.117	0.102	0.172
SiO_2	19.88	2.729	54.775	71.557	74.33
AI_2O_3	5.37	1.641	41.033	26.025	21.589
Fe_2O_3	2.86	0.064	1.48	1.255	1.009
MgO	1.52	0.598	0.349	0.108	0.244
Na_2O	0.01	-	-	-	-
K_2O	0.95	-	-	-	-
Cl	0.018	0.092	-	-	-
SO_3	2.59	0.026	0.033	0.013	0.017
TiO_2	0.31	0.004	-	0.679	0.956
MnO	0.041	0.008	0.021	0.025	0.025
P_2O_5	0.18	0.065	0.053	0.052	0.06
Loss on ignition	2.54	41.26	0.91	0.84	0.96
Physical property					
Specific gravity	3.158	2.690	2.510	2.570	2.606
Blaine's (m^2/kg)	364	581	1318	962	994

Phase composition % - cement	
C_3S	58.14
C_2S	13.22
C_3A	9.4
C_4AF	8.7

ASTM C618 requirements for pozzolanic material	**MKA**	**MKB**	**MKC**
Total of SiO_2, AI_2O_3 and $Fe_2O_3 > 70\%$	97.29	98.84	96.93
$SO_3 < 4\%$	0.033	0.013	0.017
LOI < 10%	0.91	0.84	0.96

Gypsum	> 85% purity

system to produce durable concrete depends on the durability-related transport properties attained in the systems, which needs to be investigated further. Especially since exploration of the LC^3 in Libya is still in its infancy.

This study focuses on the transport properties that indirectly define the behavior of LC³-blends throughout their service life. A detailed assessment has been conducted of the transport properties such as total porosity, water absorption due to capillary action, water permeability penetration, chloride resistance, and carbonation resistance. Mortars are made of blends with different levels of clinker replacement (%15, %30, %45) by substitution ratio of 2:1 (calcined clay: limestone). In addition, three types of calcined clays are used in order to investigate the influence of the grade of calcined clays on the transport properties of LC³-blends.

II. EXPERIMENTAL WORK

A. *MATERIALS PROPERTIES*

- *CEMENT*

The cement used in this study is Portland cement (CEM I 42.5N), manufactured by Al-Fattaih Cement Factory and conforming to the Libyan standard which mainly based on the European EN 197-1. The physical and chemical properties and phase composition of the cement used are given in Table 1.

- *LIMESTONE*

Limestone used in this study It was supplied by Al-Fattaih Cement Factory. Limestone is ground by using Los-Angeles aberration machine, this process converts lumps Limestone to powder form. after grinding, Limestone powder is collected from passing 90-micron sieve. Knowing, limestone powder is used in mixtures without thermal treatment. The physical and chemical properties of the limestone used are given in Table 1.

- *GYPSUM*

The gypsum (>85% purity) used in this study was supplied from Al-Fattaih Cement Factory. The addition of gypsum was chosen in order to prevent the system being under-sulfated for the blends.

- *CALCINED CLAY*

three different clays of varying kaolinite contents sourced from south region of Libya were used in this study. The clay produce from these places were crushed and calcined at 800 °C for 2 h. After the calcination process, the calcined clay was cooled then milled to pass on 90-micron sieve. The details of mineral clay are shown in Table 2, it was taken from a previous study by a research group from Sebha University [13]. The physical and chemical properties of calcined clays used are given in Table 1. The chemical composition of the calcined clays was compared with ASTM C 618 for its suitability to use it as a pozzolan.

Table 2: Location of clays and clays mineral

Symbol of site	**Location**	**Kaolinite content (%)**
MKA	10 km from Sebha	86
MKB	10 km from Temenhint_Sebha	55
MKC	Tarout_Wadi Shatti	48

- *AGGREGATES*

Fine aggregates used to produce the mortar cement in this study. The fine aggregate was natural sand, and its gradient falls outside the gradient limits specified in ASTM C778, but has been modified to conform to the standard sand specified in ASTM C778. The particle size distribution of fine aggregates measured by sieving test is given in Figure 1. The physical properties of fine aggregates are given in Table 3.

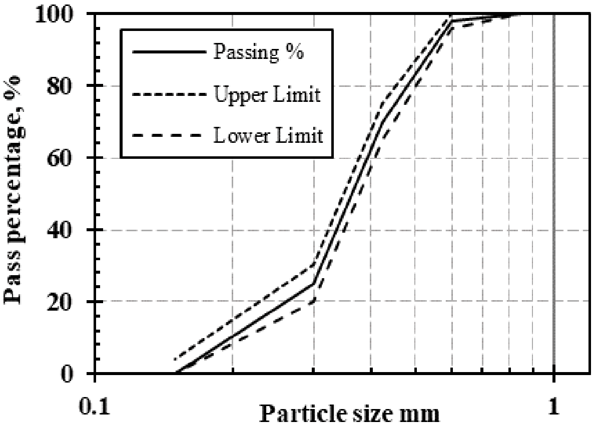

Figure 1: Particle size distribution of Fine aggregate

Table 3: physical property of Fine aggregates

Specific Gravity	Absorption (%)	Moisture Content (%)	Fineness Modulus
2.73	2	0.56	2.07

B. MIX PROPORTIONS

The Mix design for the blended cement samples consisted of looking at changes in two parameters in the sample. The first variable is the percentage of clinker replacement by calcined clay and limestone (with fixed ratio 2:1) at 15, 30 and 45%. Consequently, LC^3-80, LC^3-65 and LC^3-50 correspond to blended cements with approximately 80%, 65% and 50% of clinker content. In addition, the cement in this study was directly used as a part of clinker. Therefore, the addition of gypsum was chosen in order to prevent the system being under-sulfated for each systems composition. The second variable is the type of calcined clays used depending on the kaolinite contents in each clay type. Three type of calcined clays are used with various kaolinite contents at 86%, 55% and 48%, respectively. Therefore, ten standard mortar mixtures were prepared and used in this study according to ASTM C109, the proportions of materials for the standard mortar, one part of cement to 2.75 parts of graded standard sand by weight with a water-binder ratio of 0.485 as shown in Table 4.

C. TEST METHODS

- *WATER ACCESSIBLE POROSITY*

The porosity test was performed using the vacuum saturation method shown in Figure 2, as recommended by RILEM (1994). Three 50-mm cube specimens were tested for each test period. Testing period were 7, 28 and 90 days. The hardened cube specimens were oven-dried at 105°C until a consistent weight was achieved. The heated specimens were then allowed to cool before being weighed. The specimens were subjected to vacuum condition for 2 hours. After vacuuming, the specimens were immersed in de-aired water for 24 hours. The specimens were then taken out, wiped, and weighed in air; their weights in water were also recorded. Then, the porosity is calculated.

Figure 2: Vacuum saturation apparatus setup

Table 4: The proportions of materials for the standard mortars

Mixture ID		Cement		Calcined clay	Limestone	Gypsum addition	W/Cm*	S/Cm**
		Clinker	Anhydrite					
OPC		94	6	-	-	-	0.485	2.75
LC^3-80 (86)	**AI**	80	5.11	9.33	4.67	0.89	0.485	2.75
LC^3-80 (55)	**BI**	80	5.11	9.33	4.67	0.89	0.485	2.75
LC^3-80 (48)	**CI**	80	5.11	9.33	4.67	0.89	0.485	2.75
LC^3-65 (86)	**AII**	65	4.15	19.33	9.67	1.85	0.485	2.75
LC^3-65 (55)	**BII**	65	4.15	19.33	9.67	1.85	0.485	2.75
LC^3-65 (48)	**CII**	65	4.15	19.33	9.67	1.85	0.485	2.75
LC^3-50 (86)	**AIII**	50	3.19	29.33	14.67	2.81	0.485	2.75
LC^3-50 (55)	**BIII**	50	3.19	29.33	14.67	2.81	0.485	2.75
LC^3-50 (48)	**CIII**	50	3.19	29.33	14.67	2.81	0.485	2.75

W/Cm* - Water to cementitious ratio **S/Cm**** - Sand to cementitious ratio

- *CAPILLARY WATER ABSORPTION*

The sorptivity test (rate of absorption) of blends cement mortars was performed according to ASTM C1403. Two 50-mm cube sample were tested for each test period. Testing period were 7 and 90 days. The hardened cube sample were oven-dried at 60°C until a consistent weight was achieved. The temperature of 60°C was chosen because it allows the evaporation of the free porous water without affecting the microstructure of the samples [14]. The consistent mass is obtained for all samples between 72 and 120 hours of drying. Before weighting the samples, the dried mortar samples are covered with Pacifix silicon on four side flanges. Also, the cube sample dimensions were recorded. The specimen was placed in a container on supports and filled with water (Figure 3). The water level was maintained at 1-3 mm above the bottom of the specimen. The initial water absorption was measured by weighing the samples for up to 5 hours. Subsequently, a reading was taken once a day up to 7 days.

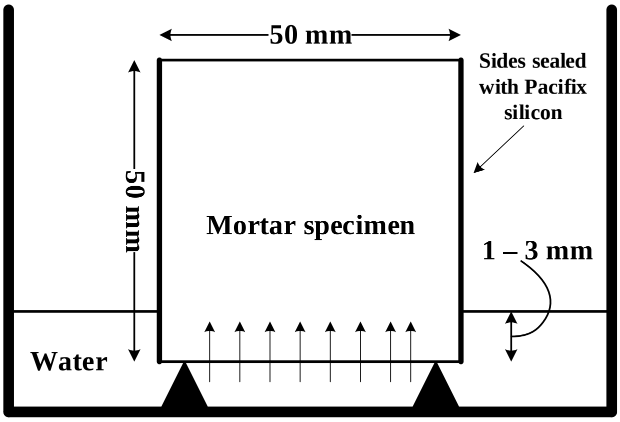

Figure 3: Schematic of rate of absorption Test

- *WATER PERMEABILITY PENETRATION*

The water penetration resistance of blends mortar samples was performed according to European standard (EN 12390-8) for determining the depth of penetration of water and permeability coefficient of each blend mortars. Figure 4 depicts the water permeability apparatus used for this test. According to this standard, the concrete sample surface must be in contact with water under 5 bar pressure for 72 hours. For each mortar mix, three Ø70 × 140 mm cylinders were cured for 28 days. It should be noted that the size of the samples is not in accordance with European Standard, and therefore, this test does not determine the true values of penetration depth, but is for the purpose of only comparing the studied mixtures. At testing day, the cylinders sample were oven-dried at 60°C until constant weight. Before being placed in the permeability testing machine, the weight of the samples was measured. They were then placed in testing machine for 72 hours. When the test was completed, the samples were weighed again to determine their mass difference. The sample is then split into two, and the depth of water penetration is measured. Three values were recorded for each sample, and the average is expressed as the water penetration depth. Thereafter, the permeability coefficient is calculated as follows:

$$K\ (m/s) = \frac{Q\ L}{A\ T\ H}$$

Where Q is the quantity of water in millimeters percolating over the period of test, L is the thickness of sample (m), A is the area of the sample (m2), T is the time in seconds over which Q is measured and H is the pressure head (m).

Figure 4: water permeability apparatus setup

- *CHLORIDE PENETRATION*

The chloride penetration resistance of blends mortar samples was investigated according to ASTM C 1556 using Ø70 × 70 mm cylinder specimens. After curing the samples in water to 28 days, all the sides of the sample were coated with waterproof Silicone in a way that only one side of the sample (the upper surface) is free for chloride penetration. thereafter, the sample was placed in a vacuum desiccator for 2 hours and then the water stopcock was opened to cover the specimen for 22 hours. After that, the specimens were taken out from the vacuum desiccator and placed in a container with 5% sodium chloride solution (with fixed the volume of the solution for all samples) for 60 day without renewal of solution (Figure 5). When the test was completed, the samples was taken out from the container and then split into two halves. the two halves were used to determine the chlorides ion along the depth with interval (0-1, 1-3, 3-5, 5-8, 8-12, 12-16, 16-20, 20-25 and 25-30 mm) as recommended by ASTM C1556 using the water-soluble method descripted in [15]. The obtained samples were ground to pass through 75 μm sieve. After that, the dust samples were oven-dried at 105°C for 2 h in an oven. About 2g of each dried sample was dispersed with 50 mL (80 °C) warm dis-tilled water in plastic container. a magnetic stirrer was used for 10 min to guarantee that the sample and dis-tilled water were well-mixed. After that, the sample was kept in plastic container for 24 h to dissolve the water-soluble chloride from the samples. The solution was then filtered using a dry Whatman filter paper number 40 into a flask. The filtrate was analyzed for chloride ions by a titration of a 0.1 M silver nitrate solution with 5% potassium chromate as an indicator, with the pH adjust-ed during the measurements by dilute sulfuric acid in order to keep pH at 9. Thereafter, the chloride diffusion coefficient $Dapp$ determining mathematically by fitting to experimentally determined chloride profile concentrations using the equation called the "error function" of Fick's second law [16].

$$C_{(x,t)} = C_s\left[1 - \operatorname{erf}\left(\frac{x}{\sqrt{4\,D_{app}\,t}}\right)\right]$$

Where $C(x,t)$ is concentration of Cl− at any depth x, Cs is the surface concentration, erf is the Gaussian error function obtained from computer, x is the distance from the exposed surface, D_{app} is the chloride diffusion coefficient and t is the exposure time.

Figure 5: The experimental setup for chloride penetration test

- *CARBONATION RESISTANCE*

The carbonation performance of blends mortars samples was investigated on 40×40×160 mm prism specimens. After 28 days of curing condition, the mortar bars were exposed to a natural atmosphere condition with natural concentration of CO_2 for 180 day (Figure 6). After 180 days of CO_2 exposure, the samples were split into two halves and the fresh surface was sprayed with a 1wt.% phenolphthalein indicator solution to determine the carbonation depth of blend mortars samples.

Figure 6: Exposure to natural carbonation (laboratory environment)

III. RESULTS AND DISCUSSION

A. *WATER ACCESSIBLE POROSITY*

The results of porosity of LC^3 blends and OPC cement mortars cured at three distinct ages are shown in Figure 7. It is clear that the porosity values for all the LC^3 blends were lower than those of the OPC at all ages. It can also be observed that the higher the replacement level of cement with limestone and calcined clay, the lower is the water-permeable absorption especially at later ages. The decrease in the porosity value of LC^3 blends could be attributed to a reduction in the total volume of capillary pores as well as increased tortuosity. The hydration products formed by the pozzolanic reaction of metakaolin in LC^3 blends are deposited in the pores and contribute to minimize the capillary porosity of the system in which the refinement of pore structure caused by pozzolanic reaction of metakaolin has been widely reported in the literature.

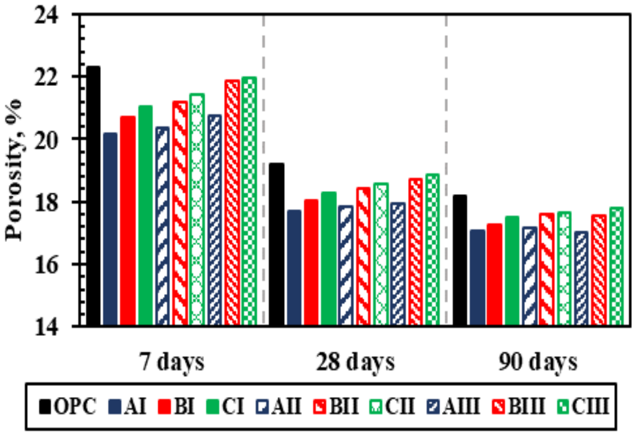

Figure 7: Porosity of OPC and LC^3 blends mortars at different ages

The correlation between compressive strength and porosity of LC^3 blends mortar are shown in Figure 8. It can be seen that with the correlation coefficient of R^2 = 0.87, the LC^3 blends mortars followed a trend similar to that of OPC mortar.

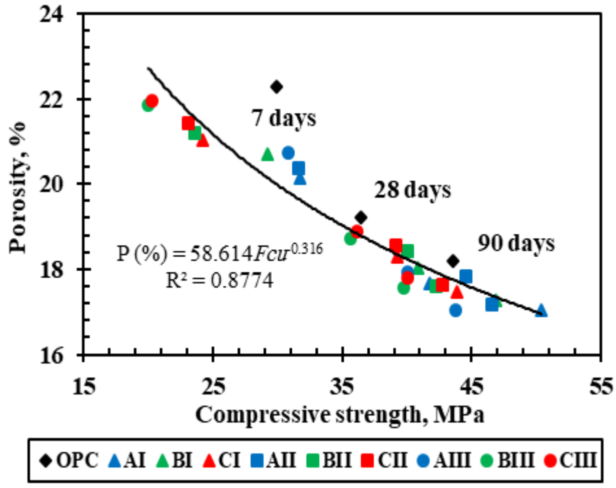

Figure 8: Relationship between the compressive strength and porosity of OPC and LC^3 blends mortars

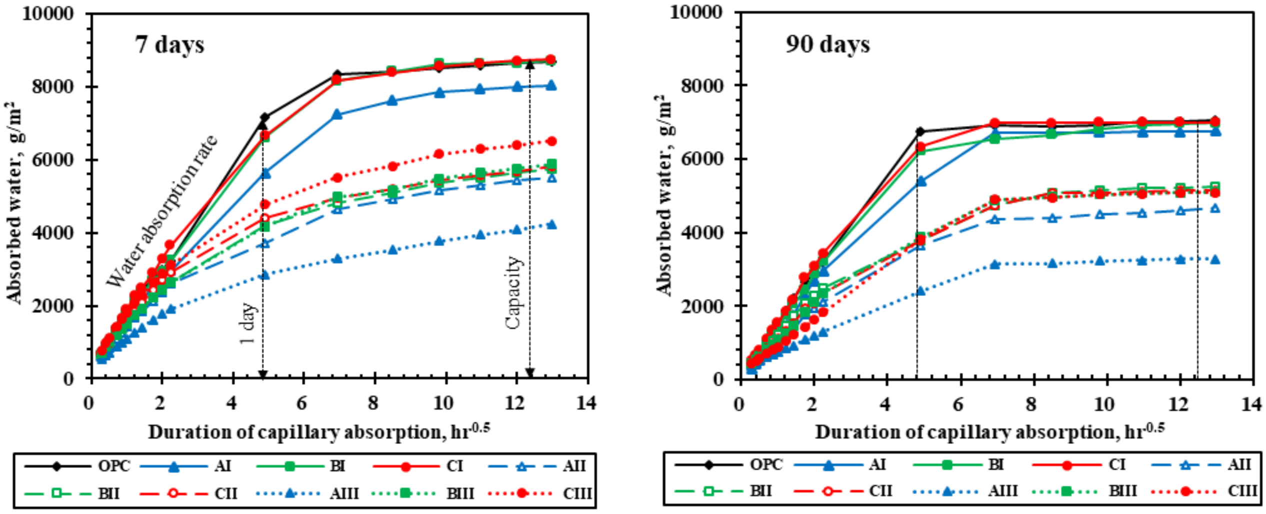

Figure 9: Capillary water absorption of OPC and LC^3 blends mortars at 7 days (Left) and 90 days (Right)

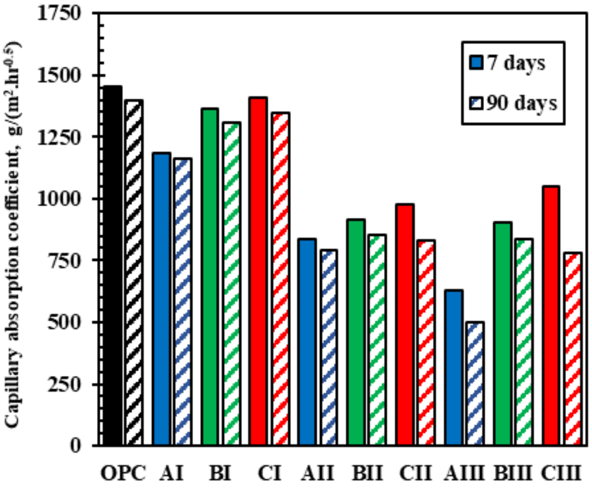

Figure 10: Capillary absorption coefficient of OPC and LC^3 blends mortars after 24 hours

B. CAPILLARY WATER ABSORPTION

Figure 9 shows the capillary water absorption curve of LC^3 blends and OPC cement mortars determined after 7 and 90 days of curing. Figure 10 shows the values of the water absorption coefficient by fitting a straight line to the water uptake of the sample in 24 hours. The water absorption rate and the capacity of absorbed water decreased for all mortars studied with increasing age. All the LC^3 blends exhibited lower water absorption rates and capacities than the OPC at all ages. It can also be observed that, the reduction in water absorption rate and capacity was inversely proportional to the increase in cement substitution by limestone and calcined clay. The reduction in values of the water absorption rate and absorbed water capacity of LC^3 blends could be attributed to a decrease in the total volume of capillary pores and the significant refinement of pore connectivity. The capillary pores present in the concrete and their connectivity are the main governing factors in the water absorption rate in concrete. Previous studies [12, 17, 18] have shown that, the number of pores corresponding to smaller size increases in LC^3 blends due to the pozzolanic reaction of calcined clay and the ongoing formation of secondary hydration products (i.e., AFm phases) which fill the voids, making the pore structure denser and less connected. These results are consistent with the results presented in Figure 9 and Figure 10.

However, it is worth mentioning that the LC^3 blends containing fairly pure metakaolin (86% kaolinite) showed lower water absorption rates than blends containing clays with 55 and 48% kaolinite. This implies that kaolinite content in LC^3 blends may increase the refinement of pore connectivity, which agree with the findings by H.Maraghech [17].

C. WATER PERMEABILITY PENETRATION

The results of the maximum and average water penetration depth (mm), and water permeability coefficient (x10^{-9} m/s) of the studied mortars determined after 28 days of curing are presented in Figure 11. It was observed that all the LC^3 blends mortars exhibited lower water permeability than the OPC. This effect was more pronounced as the calcined clay and limestone content increased. Generally speaking, the permeability of water is related to the capillary pores present in the concrete and their connectivity. This shows that the most porous composites have the highest water permeability coefficients. These findings are consistent with the results of capillary water absorption given in the previous section. However, it should be noted that the improvement in water penetration resistance increased with increasing the kaolinite content of the clays, but in general, there is not a huge gain achieved from using fairly pure calcined clay (86% kaolinite), compared with LC^3 blends containing clays with 55 and 48% kaolinite, especially in mixtures with a high substitution level.

D. CHLORIDE PENETRATION

The total chloride content profiles of the mortar samples ponded in 5% NaCl solution after 2 months of exposure are illustrated in Figure 12. It can be seen that the penetration depth as well as the chloride content at the surface decreased with increasing the level of cement replacement with limestone and calcined clay. This indicates that porosity refinement is of greater importance with respect to the impact of limestone and calcined clay on the transport of ions. Furthermore, LC^3-50 blends show the best resistance to chloride penetration. The chloride content of these systems decreased rapidly throughout the mortar depth and was negligible after 12 mm from the exposure surface after ponding for 2 months. On the other hand, the OPC mortars presented a gradual decline in chloride content from the exposure surface to a depth of up to 25 mm.

The apparent chloride diffusion coefficients of LC^3 blends and OPC cement mortars are presented in Figure 12. The diffusion coefficients of chloride ions were obtained by using non-linear regression analysis and the method of least squares of Fick's second law of diffusion according to ASTM C1556. The apparent chloride diffusion coefficient decreased as the level of cement replacement with limestone and calcined clay increased.

In contrast, a slight improvement in the apparent diffusion coefficient was observe with increasing the kaolinite content of the calcined clays. This result indicates that utilizing low-grade calcined clay has no significant effect on the apparent chloride diffusion coefficient. The significant low of chloride diffusion coefficient for LC^3 might be interpreted as a result of refinement of porosity resulted from the pozzolanic reaction. In addition, limestone and the high alumina content in calcined clay increases the high capacity of chloride binding, which bond to the chloride ions to produce Friedel's salt compared to OPC, this was confirmed in Previous investigations [17, 19].

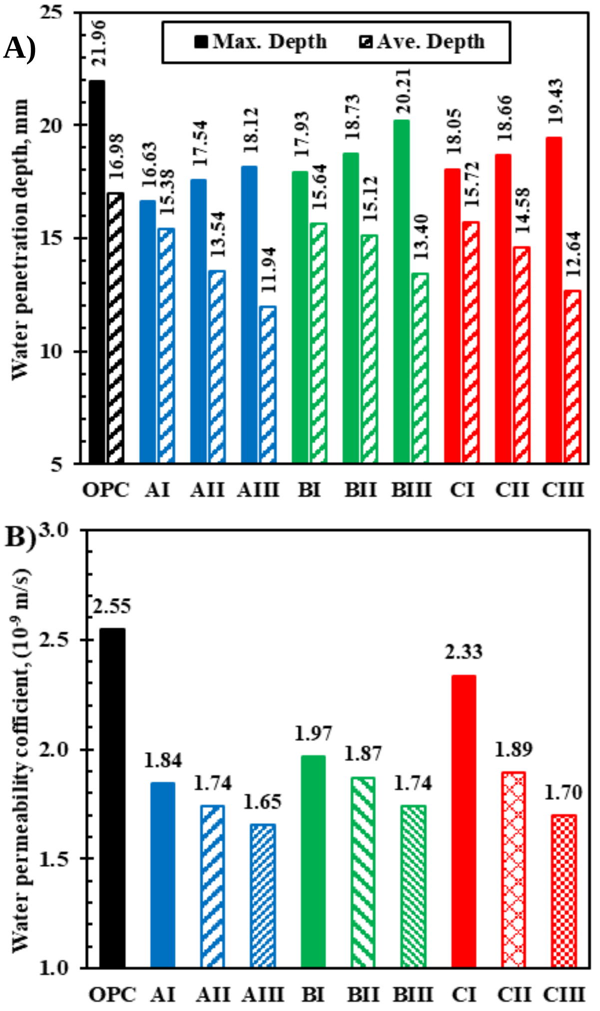

Figure 11: A) Maximum water penetration depth and B) Water permeability cofficient of OPC and LC^3 blends mortars at 28 days

E. CARBONATION RESISTANCE

Figure 13 illustrates the carbonation depths of the mortar samples after 6 months of exposure to natural carbonation, using a colorimetric pH indicator test. The results show that all LC^3 blends generally display lower

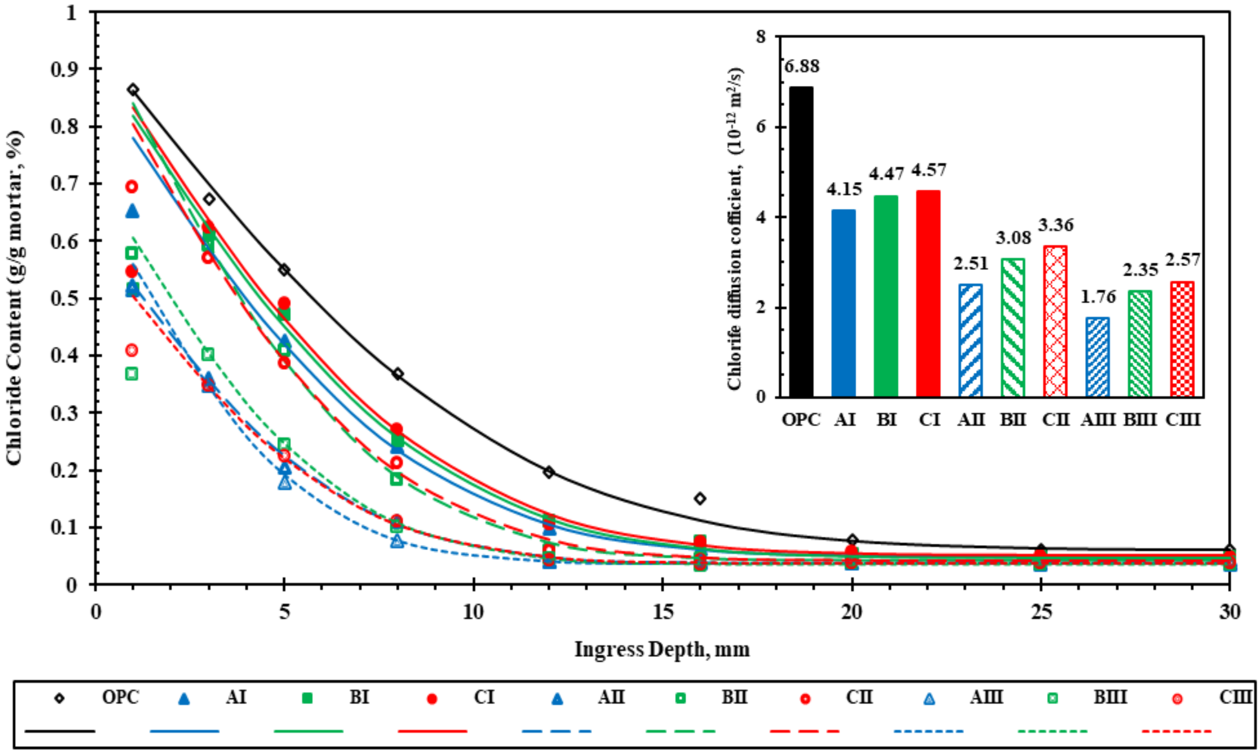

Figure 12: Total chloride content profiles and chloride diffusion coefficients in OPC and LC^3 mortars

resistance against carbonation attack compared to OPC. In general, the carbonation resistance of cement containing SCMs is generally lower as compared to OPC due to lower total alkalinity [20]. Therefore, increasing the cement substitution rate resulted in a progressive decrease in carbonation resistance. Resistance against carbonation is not dominated by porosity and pore connectivity of the mortar, which are refined in LC^3 blends compared to the OPC, as previously discussed. Carbonation is mainly influenced by the chemical composition of the blended matrix. The lower carbonation resistance of LC^3 blends can be attributed to a lack of calcium hydroxide content due to the lower amount of clinker in the blends as well as the consumption of calcium hydroxide by the pozzolanic reactions. As a result, the extent of chemical reactions that reduce CO_2 diffusion is reduced in LC^3 blends compared to OPC. Which leads to an increase in the diffusion of CO_2. However, an increase in cover depth would be required to achieve a similar service life as that of the OPC.

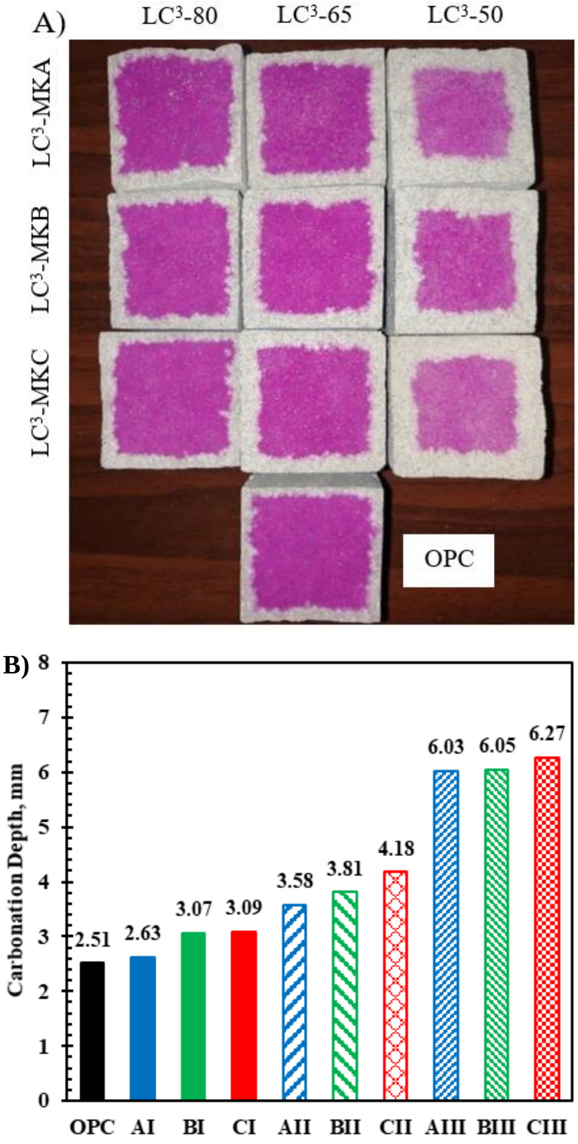

Figure 13: A) Variation in the carbonation front by colorimetric pH indicatort and B) Carbonation depths (mm) of OPC and LC^3 blends mortars for 6 months of exposure to natural carbonation

IV. CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

1. All LC^3 systems showed significantly improved results in terms of total porosity, capillary water absorption and water penetration resistance compared to OPC. Moreover, the higher the replacement of cement by limestone and calcined clay, the better the promotion of porosity refinement.
2. The apparent chloride diffusion coefficient decreased as the level of cement replacement with limestone and calcined clay increased. The improvement in chloride resistance for LC^3 blends can be attributed to its enhanced chloride binding capacity as well as the enhanced porosity refinement.
3. A slight improvement in the transport properties of LC^3 blends was observed with increasing the kaolinite content of the calcined clays. This result indicates that utilizing low-grade calcined clay has no significant effect on the transport properties of LC^3 blends, especially in blends with a high substitution level.
4. The carbonation resistance of the LC^3 blends was lower as compared to OPC. Furthermore, increasing the cement substitution rate resulted in a progressive decrease in carbonation resistance. However, at 15% replacement, the carbonation resistance of the LC^3 blend was found to nearly equal or slightly lower than the OPC. Overall, an increase in cover depth would be required to achieve a similar service life as that of the OPC, especially in blends with a high substitution level.

ACKNOWLEDGMENT

The authors would like to thank the Quality Control Laboratory at Libyan Cement Company (LCC) - Derna for offering their technical and material support. They would like to especially mention Awad Al-Zunni, Ibrahim Al-Sheari, and their team, who spared no effort to support this research.

REFERENCES

[1] H. Hilsdorf and J. Kropp, *Performance criteria for concrete durability*. CRC Press, 1995.

[2] A. M. Neville, *Properties of concrete*. Longman London, 1995.

[3] P. K. Mehta and P. J. Monteiro, *Concrete: microstructure, properties, and materials*. McGraw-Hill Education, 2014.

[4] K. P. Mehta, "Reducing the environmental impact of concrete," *Concrete international*, vol. 23, no. 10, pp. 61-66, 2001.

[5] M. C. Juenger and R. Siddique, "Recent advances in understanding the role of supplementary cementitious materials in concrete," *Cement and Concrete Research*, vol. 78, pp. 71-80, 2015.

[6] A. Mardani-Aghabaglou, G. İ. Sezer, and K. Ramyar, "Comparison of fly ash, silica fume and metakaolin from mechanical properties and durability performance of mortar mixtures view point," *Construction and Building Materials*, vol. 70, pp. 17-25, 2014.

[7] S. Sui, F. Georget, H. Maraghechi, W. Sun, and K. Scrivener, "Towards a generic approach to durability: Factors affecting chloride transport in binary and ternary cementitious materials," *Cement and Concrete Research,* vol. 124, 2019.

[8] K. L. Scrivener and R. J. Kirkpatrick, "Innovation in use and research on cementitious material," *Cement and concrete research,* vol. 38, no. 2, pp. 128-136, 2008.

[9] M. Antoni, J. Rossen, F. Martirena, and K. Scrivener, "Cement substitution by a combination of metakaolin and limestone," *Cement and Concrete Research,* vol. 42, no. 12, pp. 1579-1589, 2012.

[10] S. Krishnan and S. Bishnoi, "Understanding the hydration of dolomite in cementitious systems with reactive aluminosilicates such as calcined clay," *Cement and Concrete Research,* vol. 108, pp. 116-128, 2018.

[11] F. A. Zunino Sommariva and K. Scrivener, "Limestone calcined clay cements (LC3) : raw material processing, sulfate balance and hydration kinetics," 2020.

[12] F. Avet and K. Scrivener, "Investigation of the calcined kaolinite content on the hydration of Limestone Calcined Clay Cement (LC3)," *Cement and Concrete Research,* vol. 107, pp. 124-135, 2018.

[13] A. M. Akasha, "Using of Libyan Calcined Clay in Concrete," in *Calcined Clays for Sustainable Concrete*: Springer, 2015, pp. 555-561.

[14] M. Lion, F. Skoczylas, Z. Lafhaj, and M. Sersar, "Experimental study on a mortar. Temperature effects on porosity and permeability. Residual properties or direct measurements under temperature," *Cement and Concrete Research,* vol. 35, no. 10, pp. 1937-1942, 2005.

[15] H. Chang and S. Mu, "Detecting the Water-soluble Chloride Distribution of Cement Paste in a High-precision Way," *JoVE (Journal of Visualized Experiments),* no. 129, p. e56268, 2017.

[16] J. Crank, *The mathematics of diffusion*. Oxford university press, 1979.

[17] H. Maraghechi, F. Avet, H. Wong, H. Kamyab, and K. Scrivener, "Performance of Limestone Calcined Clay Cement (LC 3) with various kaolinite contents with respect to chloride transport," *Materials and structures*, vol. 51, no. 5, pp. 1-17, 2018.

[18] Y. Dhandapani and M. Santhanam, "Assessment of pore structure evolution in the limestone calcined clay cementitious system and its implications for performance," *Cement and Concrete Composites,* vol. 84, pp. 36-47, 2017.

[19] Z. Shi *et al.*, "Role of calcium on chloride binding in hydrated Portland cement–metakaolin–limestone blends," *Cement and Concrete Research,* vol. 95, pp. 205-216, 2017.

[20] V. Shah and S. Bishnoi, "Carbonation resistance of cements containing supplementary cementitious materials and its relation to various parameters of concrete," *Construction and Building Materials,* vol. 178, pp. 219-232, 2018.