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RESEARCH ARTICLE CONCRETE TECHNOLOGY

Effect of Limestone Calcined Clay Cement (LC^3) on Properties of Self-Compacting Concrete

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ABSTRACT

Self-Compacting Concrete (SCC) offers clear advantages in constructability and enhanced durability; however, its widespread use is often limited by high cement content and reliance on imported supplementary cementitious materials, particularly in Libya. In this context, Limestone Calcined Clay Cement (LC3) has emerged as a promising alternative for regions with abundant local clay and limestone resources. This study investigates the feasibility of incorporating LC3, produced from locally available materials within the Libyan context, into SCC as a partial replacement of Portland cement at levels of 15%, 30%, and 45%. The experimental results demonstrate that LC3-based SCC satisfies the required acceptance criteria for rheological performance, despite a gradual reduction in flowability with increasing replacement levels. Mechanical testing indicates that a moderate LC3 replacement enhances early-age strength, while higher replacement levels achieve comparable or improved strength at later ages. Tensile-related properties show no adverse effect even at the highest replacement level when compared to the reference mix. Furthermore, the observed reduction in porosity and increase in ultrasonic pulse velocity confirm improved microstructural refinement, which supports the enhancement of mechanical performance. Overall, the results confirm the technical feasibility of using LC3 in self-compacting concrete (SCC) at replacement levels up to 45% with locally sourced materials, achieving performance comparable to or better than the conventional SCC reference.

تأثير إسمنت الحجر الجيري والطين المكلَّس (LC3) على خواص الخرسانة ذاتية الدمك

سعد الفرجاني[1،*]، مسعود الطيف[1]، ابريك صداقة[1]

الملخص

تُعد الخرسانة ذاتية الدمك (Self-Compacting Concrete – SCC) من التقنيات المتقدمة في مجال الخرسانة، لما توفره من سهولة في التنفيذ وتحسين في المتانة، إلا أن استخدامها على نطاق واسع يظل محدودًا بسبب المحتوى العالي من الأسمنت واعتمادها على مواد إسمنتية مضافة مستوردة، لا سيما في ليبيا. في هذا السياق، برز إسمنت الحجر الجيري والطين المحروق (Limestone Calcined Clay Cement – LC3) كبديل واعد في المناطق التي تتوفر فيها خامات الطين الكلسي والحجر الجيري محليًا. تهدف هذه الدراسة إلى تقييم إمكانية استخدام LC3 المُنتج من مواد محلية في السياق الليبي ضمن الخرسانة ذاتية الدمك، وذلك كبديل جزئي للإسمنت البورتلاندي بنسبة 15% و30% و45%. أظهرت النتائج التجريبية أن الخرسانة ذاتية الدمك المعتمدة على LC3 تحقق متطلبات القبول الخاصة بالخواص الريولوجية، رغم الانخفاض التدريجي في قابلية الانسياب مع زيادة نسبة الاستبدال. كما بينت الاختبارات الميكانيكية أن الاستبدال المعتدل بـ LC3 يعزز المقاومة في الأعمار المبكرة، في حين تحقق نسب الاستبدال الأعلى مقاومة مكافئة أو محسّنة في الأعمار المتأخرة. ولم يُلاحظ أي تأثير سلبي على خصائص الشد حتى عند أعلى نسبة استبدال مقارنة بالخلطة المرجعية. إضافةً إلى ذلك، فإن انخفاض المسامية الكلية وازدياد سرعة نبضة الموجات فوق الصوتية يدلّان على تحسّن البنية المجهرية للخرسانة، مما ينعكس إيجابًا على أدائها الميكانيكي. وبوجه عام، تؤكد النتائج الجدوى التقنية لاستخدام LC3 في الخرسانة ذاتية الدمك حتى نسبة استبدال 45% بمواد محلية، مع تحقيق أداء مماثل أو أفضل من الخلطة الخرسانة ذاتية الدمك المرجعية.

الكلمات المفتاحية

الخرسانة ذاتية الدمك
أسمنت الحجر الجيري والطين المكلس
الانسيابية
قابلية المرور
تقنيات الخرسانة المستدامة

INTRODUCTION

Self-Compacting Concrete (SCC) represents a significant advancement in concrete technology due to its ability to flow under its own weight, its filling and passing abilities through dense reinforcement, resistance to segregation, and the ability to achieve full consolidation without the need for vibration, all of which contribute to improved construction quality and durability [1-3]. Since its development by Okamura and Ozawa in Japan in the late 1980s, SCC has been widely used in bridge substructures, precast elements, and rehabilitation works [4, 5]. In Libya, SCC has also been implemented in several engineering projects [6], particularly in reconstruction and repair activities following the Derna flood, where its ability to fill narrow sections due to heavily dense reinforcement without vibration provided clear advantages

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Table 1: Physical and chemical properties of cement, limestone, and metakaolin used in this study

Chemical composition %	Cement	Limestone	Metakaolin
CaO	63.09	55.14	5.86
SiO_2	19.88	0.03	49.07
Al_2O_3	5.37	0.54	35.18
Fe_2O_3	2.86	0.03	2.26
MgO	1.52	0.2	1.05
Na_2O	0.01	2.36	0.5
K_2O	0.95	-	-
Cl	0.018	0.092	0.15
SO_3	2.59	0.11	0.03
TiO_2	0.31	-	-
MnO	0.041	-	0.01
P_2O_5	0.18	0.2	0.06
Loss on ignition	2.54	42.03	1.02
Physical property			
Specific gravity	3.158	2.69	2.58
Blaine's fineness (m2/kg)	358	489	996

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

ASTM C618 requirements for metakaolin	MK
Total SiO_2,Al_2O_3,Fe_2O_3 > 70%	**86.51**
SO_3 < 4%	**0.03**
Loss on ignition < 10%	**1.02**

Gypsum > 85% purity

for accelerating and improving the quality of concrete placement.

Despite these benefits, the broader adoption of SCC in Libya remains limited. This is primarily due to the high cement content required to achieve adequate viscosity and stability, as well as the reliance on imported supplementary cementitious materials such as silica fume and fly ash, which are not available. Moreover, Portland cement production has a substantial environmental footprint and is estimated to contribute approximately 7–8% of global anthropogenic CO_2 emissions [7, 8]. In this context, Limestone Calcined Clay Cement (LC3) has emerged as a promising alternative that can reduce cement demand while maintaining adequate performance. LC3 is particularly suitable for regions with abundant clay and limestone deposits, offering a more economical, environmentally sustainable approach to concrete production. In addition, previous studies in Libya have verified the suitability of locally produced calcined clay for application as a supplementary cementitious material 10. Furthermore, previous studies conducted using locally sourced materials have demonstrated that LC3 can achieve satisfactory mechanical performance and improved transport properties [11, 12]. However, the behavior of LC3 in SCC may differ because SCC is highly sensitive to binder properties such as particle packing and fineness [13, 14]. Consequently, the use of LC3 in SCC may influence rheological behavior, mixture stability, and the progression of strength development

In this context, the present study investigates the use of LC3 in SCC by incorporating different clinker replacement levels (15%, 30%, and 45%) using a 2:1 substitution ratio of calcined clay to limestone. The experimental program investigates the rheological characteristics, mechanical performance properties of these mixtures in comparison with a reference OPC-based SCC. The aim is to assess the feasibility of using LC3 in SCC and to provide initial technical evidence that may support its practical implementation in construction projects in Libya, while also contributing to cost and environmental optimization.

EXPERIMENTAL WORK

Materials Properties

Cement:

Portland cement (CEM I 42.5N), produced by Al-Fattaih Cement Company (Derna, Libya) and conforming to Libyan standards based on EN 197-1, was used in this study. The physical and chemical properties of the cement are presented in Table 1.

1. Collect and crashed 2. calcined at 800 °C for a period of 2h 3. Grinded and sieved 90-micron

Figure 1: Shape of metakaolin and the steps involved in its processing

Metakaolin:
The metakaolin used in this study was sourced from a quarry located in southern Libya, along the Sabha–Tamanhint road, approximately 10 km from the city of Sabha. The kaolin clay was crushed and calcined in a furnace at 800 °C for two hours. After calcination, the metakaolin was allowed to cool, ground into a fine powder using a Los Angeles abrasion machine, and passed through a 90 µm sieve. Figure 1 illustrates the shape of metakaolin, and the processing steps used, while Table 1 presents its physical and chemical properties.

Limestone:
The limestone used in this study was sourced from a quarry located near Derna. The material was ground into a fine powder using a Los Angeles abrasion machine and then passed through a 90 µm sieve. The physical and chemical properties of the limestone powder are presented in Table 1.

Aggregate:
The Coarse aggregate used in this study was crushed limestone with a maximum nominal size of 12.7 mm, while the fine aggregate was natural sand. Both aggregates were supplied from a quarry located near Derna and conformed to ASTM C33 specifications. The specific gravity of the coarse and fine aggregates was 2.63 and 2.71, respectively. The water absorption of the coarse and fine aggregates was 2.35% and 1.02%, respectively, and the required absorption water was included in the total batch water to maintain the target effective water content. The particle size distribution (grading) of both fine and coarse aggregates is presented in Figure 2.

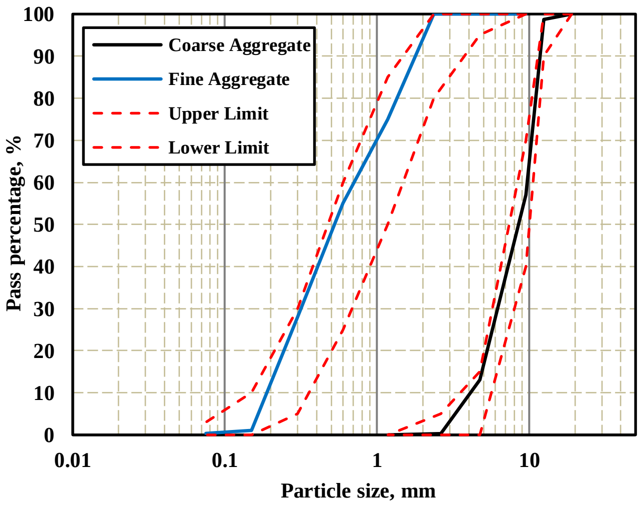

Figure 2: Particle size distribution of fine and coarse aggregates

Chemical Admixtures:
This study was limited to a single type of chemical admixture, a high-range water-reducing plasticizer commercially known as DEGAST AS 2255, of Turkish origin. Based on polycarboxylate ether (PCE) technology, the admixture provides high water-reduction efficiency and improved workability and conforms to the requirements of ASTM C494. The properties of the plasticizer are summarized in Table 2.

- **Mixing proportions and SCC production**

The mixtures were designed to have a total binder level of approximately 500 kg/m^3 and water/binder ratio of 0.35. The dosage of the superplasticizer was changed to obtain a flow between 650 and 700 mm. The cement replacements by additives were carried out by weight. Therefore, the paste volume and the amount of fines and aggregates varied according to the level of additives due to differences in the specific masses of the materials.

Table 2: Properties of the plasticizer used in this study

Chemical composition	Polycarboxyate based
Density (g/cm³)	1.06 ± 0.02
pH	7 – 3
Color and form	Brown liquid
Dosage	0.6 – 1.8% of cement
Standards	ASTM C494 Type F, and TS-EN 934-2

Four self-compacting concrete (SCC) mixes were prepared, including one reference mix made with ordinary Portland cement, denoted as SCC-OPC, and three LC3-based mixes. The LC3 mixtures incorporated cement replacement levels of 15%, 30%, and 45%, denoted as SCC-LC3-15, SCC-LC3-30, and SCC-LC3-45, respectively. For all LC3 mixes, a constant mass ratio of 2:1 between calcined clay and limestone was adopted. The mix design procedure complies with the recommendations of ACI 237R for self-compacting concrete [1]. Detailed mixture proportions are summarized in Table 3.
All concrete mixtures were prepared following a consistent mixing procedure comprising four main steps, as illustrated in Figure 3. First, the binder materials (cement and SCMs), along with the coarse and fine aggregates, were introduced into the mixer and dry-mixed for approximately 1 minute to ensure uniform distribution. Second, 70% of the total mixing water was added, and the mixture was mixed for 2 minutes. Third, the superplasticizer was mixed with the remaining 30% of the water and then added to the mixer, followed by mixing for 1 minute until a homogeneous mixture was obtained. Finally, the mixer was stopped to allow the mixture to rest for 1 minute, after which mixing was resumed for an additional 1 minute. The total effective mixing time was 6 minutes. This mixing procedure was applied to all concrete mixtures investigated in this study. Upon discharging from the mixer, the fresh properties of each mixture were evaluated through self-compaction tests. The fresh concrete was then placed into the moulds and compacted without any vibration. Finally, surface finishing was carefully performed to obtain a smooth and uniform surface.

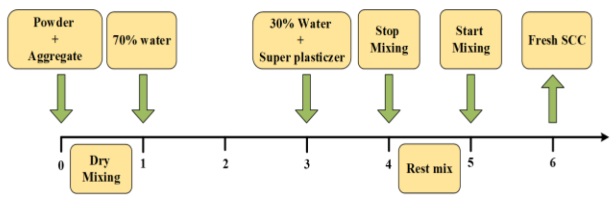

Figure 3: Mixing procedure used for preparing concrete mixtures

- **Fresh state tests**

In the fresh state, the self-compacting concrete (SCC) mixtures were evaluated using slump flow diameter, flow time (T_{50cm}), V-funnel, L-box, and J-ring tests. The fresh concrete tests were conducted immediately after approximately 5 minutes of complete mixing. Slump flow, T50cm, V-funnel, and L-box tests were performed in accordance with the EFNARC guidelines for self-compacting concrete [3], while the J-ring test was carried out following the recommendations of ACI 237R-07 [1]. These tests were employed to assess the filling ability, passing ability, and segregation resistance of the SCC mixtures.

Table 3: Mixture proportions of the concrete mixes used in this study

MIX ID		SCC-OPC	SCC-LC3-15	SCC-LC3-30	SCC-LC3-45
Cement, (kg/m^3)		500	425	350	275
LimeStone, (kg/m^3)		-	25	50	75
Metakaolin, (kg/m^3)		-	50	100	150
Coarse aggregate, (kg/m^3)		813.09	806.9	800.71	794.53
Fine aggregate, (kg/m^3)		894.4	887.59	880.78	873.98
Water, (Lit)		175	175	175	175
Superplasticizer (SP), % to bender		1.6	1.8	1.9	2
ACI237R recommendations					
powder content	**≥385**	500	500	500	500
water/binder (w/b)	**0.32-0.45**	0.35	0.35	0.35	0.35
Absolute volume of coarse aggregate	**28 - 32%**	30.92%	30.68%	30.45%	30.21%
Paste fraction	**34-40%**	36.08%	36.46%	36.84%	37.22%
Mortar fraction	**68-72%**	69.08%	69.21%	69.34%	69.47%

- Slump flow and T50cm tests were conducted to assess the flow characteristics of fresh concrete by measuring the spread diameter immediately after cone removal and the time required to reach a 500 mm diameter, as shown in Figure 4a.
- The J-Ring slump flow and blocking index test was conducted to evaluate the passing ability and potential blockage of fresh SCC through reinforcement. The concrete was poured into the slump cone placed inside the J-Ring, and the cone was lifted to allow the concrete to flow. The spread diameter was measured, and the blocking index was calculated as the difference between the slump flow with and without the J-Ring. The test setup is shown in Figure 4b.
- The V-funnel test was conducted to evaluate the flowability, passing ability, and segregation resistance of fresh SCC. The vertical section of the V-funnel was filled, and the gate was immediately opened to allow the concrete to flow out. The time required for the concrete to pass through the lower opening was recorded, ending when light became visible at the bottom. The V-funnel setup is shown in Figure 4c.
- The L-box test was used to assess the ability of fresh concrete to flow through obstructions. The fillability was evaluated by comparing the concrete height at the outlet to the concrete height at end of the L-box. The apparatus includes vertical and horizontal sections separated by a gate with three evenly spaced rods. Once the vertical section was filled, the gate was opened to allow concrete to flow, and the heights were recorded. The setup is illustrated in Figure 4d.

(a) (b) (c) (d)

Figure 4: Fresh-state testing of SCC mixtures, (a) slump flow, (b) J-ring tests, (c) V-funnel, and (d) L-box

Figure 5: Apparatus used for compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV) tests of concrete specimens

- **Hardened state tests**

In the hardened state, the SCC mixtures were evaluated at different curing ages to characterize their mechanical behavior, and pore structure properties. Detailed descriptions of the test procedures and conditions are provided in the following sections:

- Compressive strength, ultrasonic pulse velocity (UPV), and splitting tensile strength tests were conducted on cylindrical concrete specimens with a diameter of 70 mm and a height of 140 mm. The tests were performed at curing ages of 3, 7, 28, and 90 days. The average of three specimens was considered for each age. The tests were carried out in accordance with ASTM C39/C39M, ASTM C597, and ASTM C496/C496M, respectively, the test setups are illustrated in Figure 5.
- Flexural strength tests were conducted on prismatic concrete specimens with dimensions of 100×100×400mm. The tests were performed at a curing age of 28 days, and the reported results represent the average of three specimens for each mix. The flexural strength was determined using the three-point bending method in accordance with ASTM C293/C293M. The test setup and loading configuration are illustrated in Figure 6.
- Total porosity was determined in accordance with RILEM (1994) using the vacuum saturation method to assess the pore structure of concrete, shown in Figure 7. Cylindrical specimens with a diameter of 70 mm and a height of 140 mm were tested at curing ages of 7, 28, and 90 days. Before testing, the specimens were oven-dried at 105 °C until a constant mass was obtained. After drying, the specimens were allowed to cool to laboratory temperature and then weighed. Subsequently, the specimens were placed under vacuum conditions for 1 h to remove entrapped air from the pore system. Following the vacuum stage, the specimens were immersed in de-aired water for 24 h to ensure full saturation. The saturated specimens were then removed, surface-dried, and weighed in air, after which their apparent mass in water was recorded. Based on these mass measurements, the total porosity was calculated.

Figure 6: Three-point bending test setup for flexural strength

Figure 7: Total porosity test setup for concrete specimens

RESULTS AND DISCUSSION

- **Slump flow and T50cm**

Figures 8a and 9 present the results of the Slump Flow and T50cm spread time tests, along with the corresponding spread diameters for all the mixes studied, respectively. It is observed that increasing the LC3 replacement ratio led to a gradual decrease in flow and an increase in spread time compared to the reference mix; the spread diameter reduced from 715 mm in the reference mix to around 655 mm at the highest replacement, and the T50cm increased from 3 to 5 seconds. With the W/B ratio kept constant, this reduction in flowability and increase in

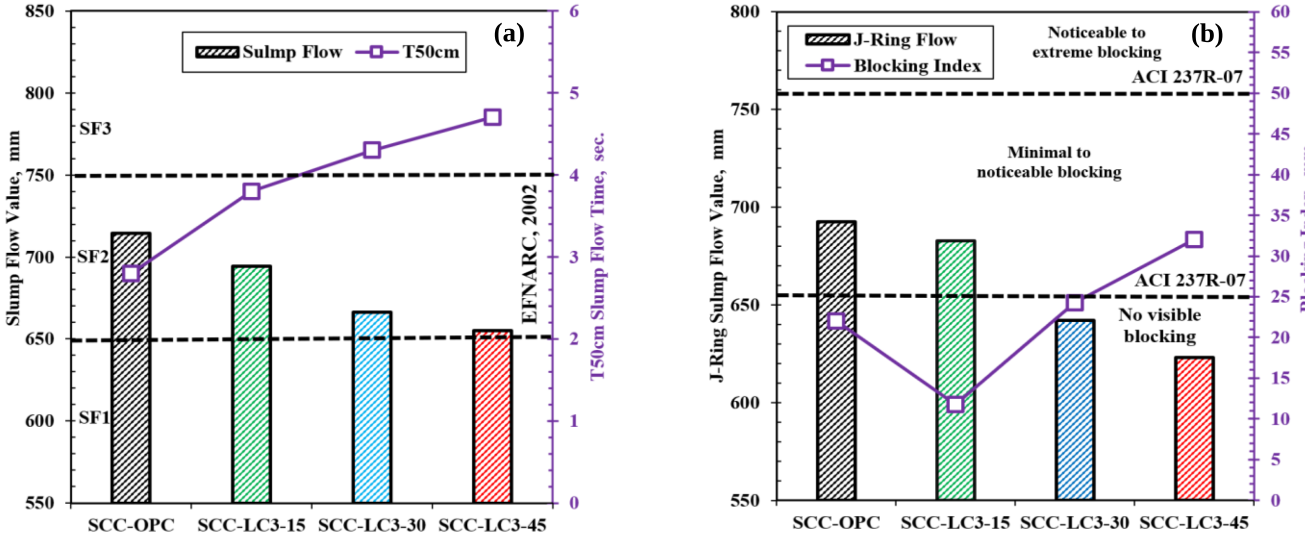

Figure 8: (a) Results of Slump Flow and T50cm spread time tests, (b) J-Ring Slump Flow and Blocking Index for all mixes studied

SCC-OPC **SCC-LC3-15** **SCC-LC3-30** **SCC-LC3-45**

Figure 9: Spread diameters for all the mixes studied

spread time can be attributed to the higher content of fine materials, where metakaolin (MK) is characterized by a high surface area and an irregular particle structure, which leads to increased water absorption and higher viscosity of the paste, thereby contributing to enhanced cohesion of the mix and reducing the self-flowing speed of the concrete [15 ,16]. In contrast, limestone powder acts as a fine filler, improving particle packing; however, its increase at higher replacement ratios may increase internal friction between particles and reduce flowability [14 ,16]. Despite the reduced flowability, all mixes remain within EFNARC's acceptable limits for both Slump Flow and T50cm [17], indicating the feasibility of using LC3 at replacement ratios up to 45% in SCC concrete with adequate workability if the mix design is well-controlled.

- **J-Ring slump flow and blocking index test**

Figures 8b present the results of the J-Ring Slump Flow and Blocking Index tests for the mixes studied. It is observed that increasing the LC3 replacement ratio led to a gradual reduction in flowability and an increase in blocking behavior. Specifically, the J-Ring Slump Flow value decreased from approximately 680 mm for the reference mix to around 620 mm at the highest replacement, while the Blocking Index increased from about 22 mm to over 32 mm, indicating a shift from no visible blocking to minimal noticeable blocking. Despite these changes, all mixes remain within the acceptable limits of the ACI 237R-07 guideline. These results confirm the trend observed previously, where the increase in fine materials, such as metakaolin and limestone, resulted in higher viscosity and internal friction, consequently reducing

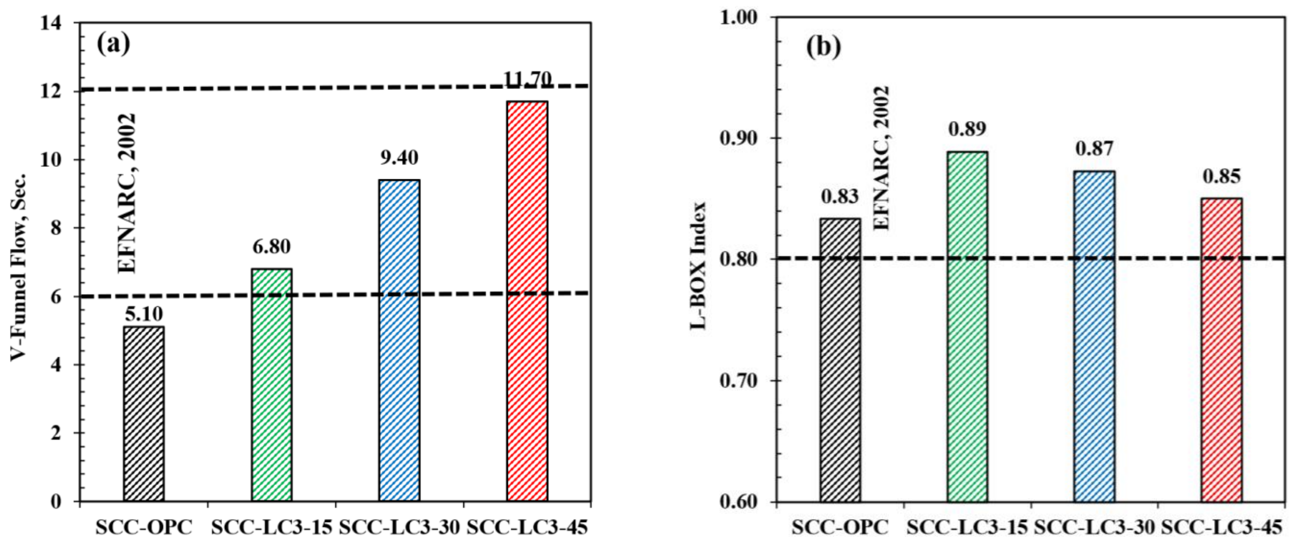

Figure 10: (a) V-Funnel flow time and (b) L-Box passing ability results for all mixes studied

flowability and increasing blocking.

- **V-funnel and L-box test**

Figures 10a and 10b illustrate the results of the V-Funnel flow time and L-Box passing ability index for all SCC mixes studied. A clear trend is observed in which increasing the LC3 content leads to a progressive increase in V-Funnel flow time and a slight reduction in the L-Box ratio, indicating increased mixture viscosity and reduced passing ability with higher LC3 replacement levels. This behavior is consistent with the trends observed in the other fresh-state tests. The reduction in Slump Flow diameter, the increase in T50cm spread time, and the higher blocking Index test collectively reflect a progressive decrease in flow mobility as the LC3 replacement level increases. In this context, the smaller spread diameters and longer flow times observed previously are directly reflected in the longer V-Funnel discharge times and lower L-Box ratios. The coherence of these results confirms that increasing LC3 replacement leads to a gradual reduction in flow mobility across the fresh-state tests. Despite these changes, all measured values remain within the acceptance limits specified by EFNARC (2002), indicating that the rheological properties of SCC are maintained up to 45% LC3 replacement.

- **Compressive strength**

Figure 11a illustrates the development of compressive strength for all SCC mixes studied at curing ages of 3, 7, 28, and 90 days. All mixes exhibited a continuous increase in compressive strength with curing time. At early ages, the SCC-LC3-15 mix exhibited higher compressive strength than the reference SCC-OPC mix, whereas mixes with higher LC3 replacement levels showed lower early-age strength, with the reduction becoming more pronounced as the replacement level increased due to the reduced clinker content and dilution effect [17, 18]. At later ages, a noticeable improvement in compressive strength was observed for the SCC-LC3 mixes, owing to the pozzolanic reaction of metakaolin and the synergistic interaction between limestone and aluminates, which enhances matrix densification and strength development [18, 19]. Moreover, the limited late-age strength development at higher replacement levels may be attributed to reduced portlandite availability and decreased clinker hydration due to high limestone and calcined clay dosages. This aligns with [20], which reported a loss of linearity between strength and kaolinite content at later ages. Overall, the results indicate that although the highest LC3 replacement level exhibits lower compressive strength at early ages, it achieves higher compressive strength than the reference OPC-based SCC at later ages, demonstrating improved long-term strength development.

- **Splitting tensile strength**

Results of the splitting tensile strength of the LC3-based SCC mixes and the reference SCC-OPC at different curing ages up to 90 days are presented in Figure 11b. At early ages, the splitting tensile strength generally followed the same trend observed for compressive strength, where SCC-LC3-15 exhibited higher tensile strength than the reference mix, while higher LC3 replacement levels showed lower early-age tensile strength. The enhancement at 15% replacement can be attributed to improved particle packing and filler effects, providing additional sites for hydration products to form, which promote a denser and more continuous matrix and strengthen the paste–aggregate interface, thereby benefiting tensile-related properties. Similar mechanisms and strength gains at moderate LC3 contents have been widely reported for LC3 systems [18, 21]. In contrast, the reduced early-age tensile strength at higher replacement levels is consistent with clinker dilution and lower portlandite availability, which can temporarily limit hydration progress and delay strength gain[18, 19]. With increasing curing time, a gradual improvement in splitting tensile strength was observed for all LC3 mixes, reflecting continued pozzolanic and limestone–calcined clay synergistic reactions that refine pores and densify the microstructure, enhancing crack resistance at later ages [21]. Consequently, at 90 days, all LC3 mixes showed higher or nearly equal splitting tensile strength compared to the control mix, in line with long-term microstructural refinement reported for LC3 systems [22].

- **Flexural strength**

Figure 12 illustrates the flexural strength of the SCC mixes at a curing age of 28 days. A trend consistent with the splitting tensile strength results is observed, where the SCC-LC3-15 mix exhibits a clear improvement relative to the reference SCC-OPC, whereas higher LC3 replacement levels (30–45%) show a moderate reduction. Nevertheless, flexural strength remains comparable to the control even at 45% replacement, which further confirms—as discussed for splitting tensile strength—that LC3 incorporation does not adversely affect the tensile-related performance of SCC.

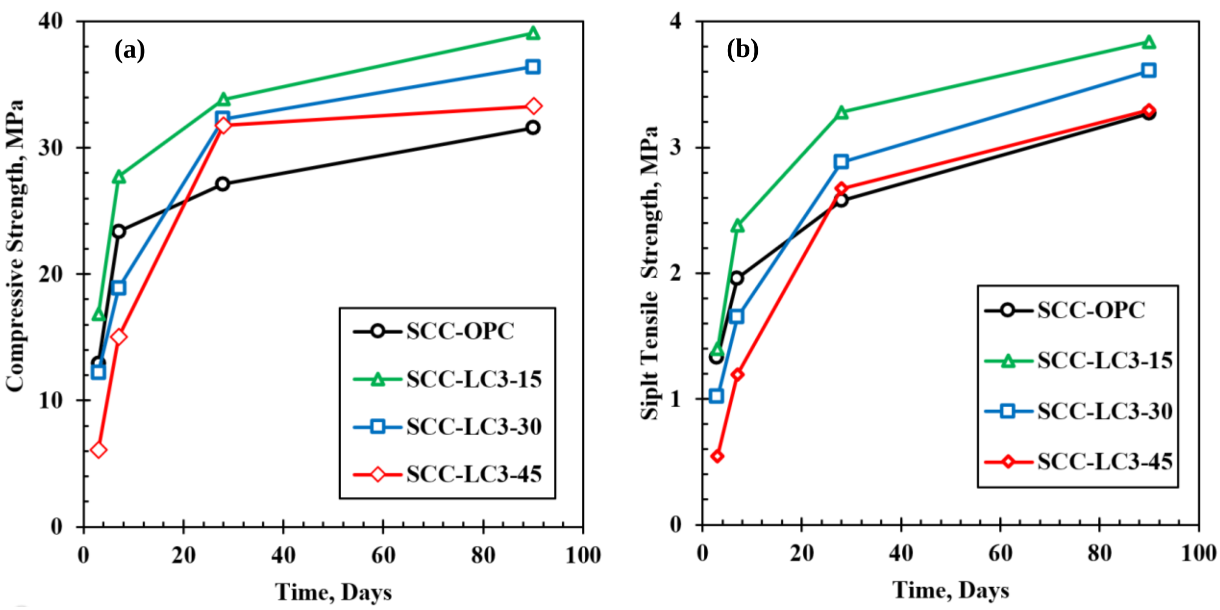

Figure 11: (a) Compressive strength and (b) splitting tensile strength of SCC mixes at different curing ages

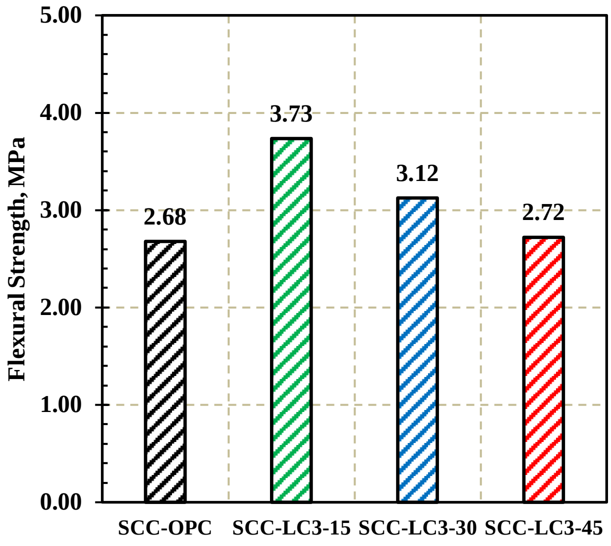

Figure 12: Flexural strength of SCC mixes at 28 days

- **Total porosity and UPV test**

Figure 13 presents the variation of porosity and ultrasonic pulse velocity (UPV) of SCC mixes with different LC3 replacement levels. With increasing LC3 content, a general reduction in porosity accompanied by an increase in UPV is observed, particularly at higher replacement levels and later curing ages, indicating progressive pore refinement and microstructural densification, which has also been reported in the literature [19, 23 24]. From a mechanical-performance perspective, these microstructural indicators are consistent with the strength trends discussed earlier. Mixes exhibiting lower porosity and higher UPV generally reflect improved matrix continuity and fewer internal defects, which correlates with the observed development in compressive strength and tensile-related properties, especially at later ages.

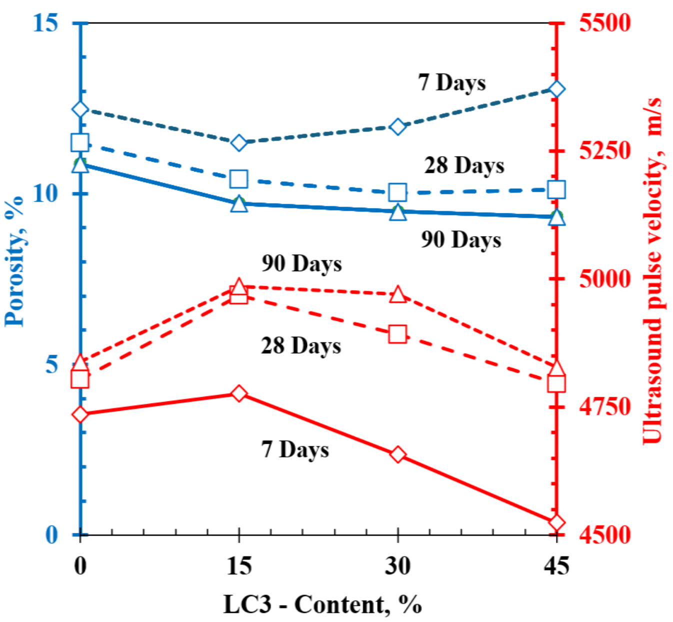

Figure 13: Porosity and ultrasonic pulse velocity (UPV) of SCC mixes with different LC3 replacement levels

The clear positive correlation between compressive strength and UPV, together with the inverse relationship between compressive strength and porosity shown in Figure 14, confirms that the mechanical enhancement of LC3-based SCC is closely governed by improved matrix continuity and densification. Overall, the results demonstrate that the incorporation of LC3 effectively refines the pore structure, leading to enhanced mechanical properties.

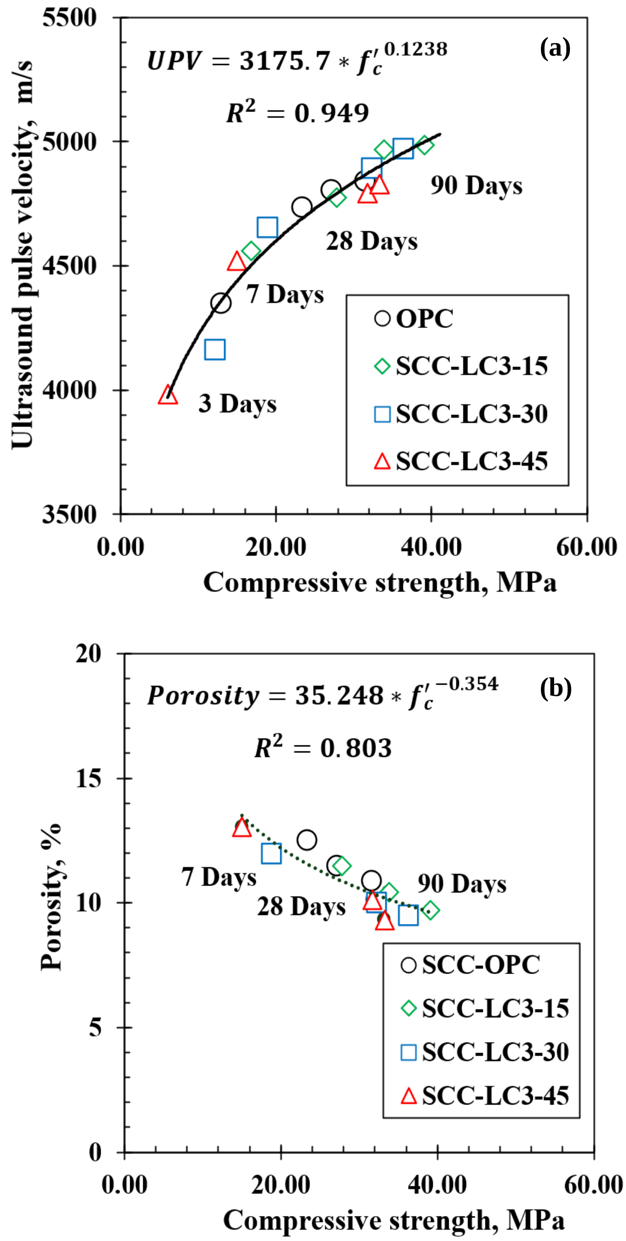

Figure 14: Relationship between compressive strength and (a) UPV and (b) porosity of LC3-based SCC mixes

CONCLUSIONS

This study investigated LC3-based self-compacting concrete (SCC) with cement replacement levels up to 45%, focusing on fresh-state behavior, mechanical performance, and microstructural characteristics. Based on the experimental results, the following conclusions can be drawn:

1. Increasing LC3 replacement led to a gradual reduction in flowability, reflected by lower slump flow diameters and higher T50cm, V-funnel flow times, and blocking indices. Nevertheless, all SCC mixes satisfied the acceptance criteria specified by EFNARC and ACI 237R-07, confirming that adequate self-compactability can be maintained up to 45% LC3 replacement with proper mix design.

2. In terms of compressive strength development, a moderate LC3 replacement level (15%) resulted in higher early-age compressive strength compared to the reference SCC-OPC, whereas higher replacement levels led to reduced early-age strength. However, at later ages, all LC3-based mixes exhibited enhanced strength development, with the highest replacement level attaining compressive strength exceeding that of the reference mix, reflecting the beneficial contribution of pozzolanic reactions and matrix densification.
3. Splitting tensile and flexural strengths followed trends consistent with compressive strength. Moderate LC3 replacement improved tensile performance, whereas higher replacement levels exhibited only a slight reduction at early ages. However, at later ages, even the highest LC3 replacement level developed tensile strength comparable to that of the reference SCC.
4. The reduction in total porosity and the corresponding increase in ultrasonic pulse velocity indicate an improvement in the microstructural characteristics of LC3-based SCC, particularly at higher replacement levels and later curing ages. This microstructural refinement is closely associated with enhanced matrix continuity, which in turn supports the observed improvements in mechanical performance.

Overall, the results demonstrate that LC3-based cement can be effectively incorporated in SCC at replacement levels up to 45%, achieving acceptable fresh-state performance and enhanced long-term mechanical properties, supported by improved microstructural refinement.

RECOMMENDATIONS

Based on the findings that LC3-based SCC—particularly at 45% replacement—achieved performance comparable to or better than the reference SCC while meeting fresh-state acceptance criteria, future work should focus on three complementary directions. First, long-term durability should be evaluated under Libyan exposure conditions, including chloride and sulfate resistance. Second, pilot-scale field trials are recommended to verify constructability and quality control under practical casting conditions. Finally, the potential embodied CO_2 savings should be quantified through life-cycle assessment (LCA). Collectively, these efforts would establish a robust basis for the practical implementation of LC3-based SCC in Libya.

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