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Sustainable Self-Compacting Concrete: The Role of Limestone Powder as A Cement Replacement

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Abstract

The excessive use of cement in concrete production contributes significantly to environmental impacts, particularly CO_2 *emissions. One potential solution is the partial replacement of cement with limestone powder in self-compacting concrete (SCC). This study aimed to investigate the effect of limestone powder as a partial cement replacement on the fresh properties and compressive strength of SCC. Limestone powder was used at replacement levels of 0%, 6%, 9%, 12%, and 15% by weight of cement. The fresh properties of SCC were evaluated using slump flow, V-funnel, and L-box tests, while compressive strength tests were conducted to assess hardened performance. The results showed that SCC mixtures containing up to 9% limestone powder satisfied the SCC workability requirements. The optimum performance was achieved at 6% limestone powder replacement, which produced a slump flow diameter of 600 mm and compressive strength of 29.58 MPa, exceeding the design strength target of 25 MPa. Higher replacement levels reduced both workability and compressive strength, with the 15% mixture failing to meet acceptable performance criteria. These findings indicate that limestone powder can be effectively utilized as a sustainable partial cement replacement in SCC at moderate replacement levels while maintaining satisfactory fresh and hardened properties.*

Keywords: *self-compacting concrete; limestone powder; workability; compressive strength; sustainable construction.*

Abstrak

Penggunaan semen yang berlebihan dalam produksi beton memberikan dampak lingkungan yang signifikan, terutama terhadap peningkatan emisi CO_2*. Salah satu solusi yang dapat diterapkan adalah penggunaan limestone powder sebagai pengganti sebagian semen pada self-compacting concrete (SCC). Penelitian ini bertujuan untuk menganalisis pengaruh penggunaan limestone powder sebagai pengganti sebagian semen terhadap sifat segar dan kuat tekan SCC. Limestone powder digunakan dengan variasi kadar penggantian sebesar 0%, 6%, 9%, 12%, dan 15% dari berat semen. Pengujian sifat segar SCC dilakukan menggunakan slump flow, V-funnel, dan L-box, sedangkan pengujian kuat tekan dilakukan untuk mengevaluasi sifat mekanis beton. Hasil penelitian menunjukkan bahwa campuran SCC dengan kadar limestone powder hingga 9% masih memenuhi persyaratan workability SCC. Kinerja optimum diperoleh pada variasi 6% limestone powder dengan nilai slump flow sebesar 600 mm dan kuat tekan sebesar 29,58 MPa, yang melebihi kuat tekan rencana sebesar 25 MPa. Peningkatan kadar limestone powder yang lebih tinggi menyebabkan penurunan workability dan kuat tekan, dengan campuran 15% tidak memenuhi kriteria performa yang dipersyaratkan. Temuan ini menunjukkan bahwa limestone powder dapat dimanfaatkan secara efektif sebagai bahan pengganti sebagian semen yang lebih berkelanjutan pada SCC, khususnya pada kadar penggantian sedang, tanpa mengurangi sifat segar dan sifat mekanis beton secara signifikan.*

Kata kunci: *self-compacting concrete; bubuk kapur; kelecakan; kuat tekan; konstruksi berkelanjutan*

INTRODUCTIONS

The global cement industry remains one of the most carbon-intensive sectors in modern construction, responsible for an estimated 7–8% of total annual anthropogenic CO_2 emissions [1], [2]. The main driver of this footprint lies in clinker production, a process that requires high-temperature calcination of limestone and inherently releases large amounts of CO_2 from raw material decomposition [3]. In response to increasing environmental pressures and international commitments to carbon reduction, there is a growing emphasis on developing sustainable concrete technologies that can reduce cement content without sacrificing performance [4]. Self-compacting concrete (SCC), characterized by its ability to flow and consolidate under its weight without mechanical vibration, offers a unique platform for integrating alternative binders and inert fillers [5], [6]. Among these, limestone powder (LP) has attracted significant interest due to its widespread availability, low cost, and potential to improve certain performance aspects of concrete while lowering its environmental impact. LP can act as a physical filler, enhancing particle packing and potentially accelerating early hydration, making it an attractive candidate for partial cement replacement in SCC formulations [7].

Over the past decade, multiple studies have evaluated the influence of LP on the properties of SCC [8], [9], [10], [11]. Research has shown that incorporating LP in moderate amounts—commonly in the range of 7–10% by weight of cement—can improve the fresh properties of SCC [7]such as flowability and segregation resistance, due to better particle-size distribution and the so-called "filler effect." In some cases, slight improvements in compressive strength have been reported, attributed to enhanced matrix densification and the provision of nucleation sites for hydration products [12]. Burroughs et al (2017) in [13] has demonstrated that such benefits are most pronounced when LP is finely ground and evenly distributed within the matrix. However, it is also widely recognized that excessive LP replacement, particularly beyond 15%, can result in a dilution effect, where the reduction in reactive clinker compromises strength development [14]. These effects are strongly dependent on LP fineness, cement-to-filler ratio, and the presence of chemical admixtures [7]. In SCC, the use of high-range water-reducing admixtures, such as superplasticizers, is critical to maintain the required rheology when cement content is partially substituted, ensuring that workability is preserved without excessive water addition [15].

Despite substantial prior work, there are still important knowledge gaps regarding the optimal replacement level of LP in SCC mixtures designed with superplasticizers, especially when both fresh properties and compressive strength performance. Many earlier studies have evaluated multiple performance parameters simultaneously—such as slump flow, passing ability, and durability—without isolating compressive strength as the sole measure. Furthermore, the range of LP replacement levels investigated in past research has often been relatively coarse, focusing on one or two substitution points rather than a systematic series of incremental levels. This limits the ability to identify the precise threshold at which beneficial effects transition into performance decline. Additionally, few studies have directly linked changes in fresh properties and compressive strength to specific replacement percentages in SCC mixtures that also contain a modern superplasticizer dosage, which may significantly influence hydration dynamics and particle dispersion [16], [17]. Understanding this interaction is crucial for practical application, as SCC's success in construction relies heavily on both fresh and hardened performance, and compressive strength remains one of the most critical parameters for structural acceptance.

Considering these gaps, the present study investigates the effect of LP substitution at five levels: 0%, 6%, 9%, 12%, and 15% by weight of cement in SCC mixtures containing a consistent superplasticizer dosage, on the fresh properties and compressive strength of SCC. The fresh properties were evaluated using slump flow, V-funnel, and L-box tests, while compressive strength tests were conducted to assess hardened performance. This targeted approach enables a more detailed understanding of the relationship between LP content and SCC properties, without confounding effects from other performance indicators. By systematically analyzing strength results across different ages, the study aims to determine the optimal LP replacement percentage that maintains or enhances compressive strength while reducing cement. The novelty of this work lies in its integrated consideration of replacement increments, controlled admixture conditions, and combined evaluation of fresh and hardened SCC properties, thereby filling an important research gap in sustainable SCC development. The findings are expected to provide practical guidelines for the concrete industry, supporting the transition to low-carbon construction materials in line with global decarbonization goals.

METHODOLOGY

This study adopts an experimental approach to investigate the effect of incorporating LP as a partial cement replacement, along with a fixed dosage of superplasticizer, on the compressive strength of

SCC. In addition, the study also evaluates the fresh properties of SCC, including filling ability, passing ability, and segregation resistance. The research procedure involves material characterization, mix design, specimen preparation, curing, and compressive strength testing by relevant standards.

Materials and Material Testing

1. Cement

The cement used in this study is Portland Cement Type I (Tonasa brand), which meets the requirements of ASTM C150-92 for physical and chemical properties.

2. Coarse Aggregates

Crushed stone with a maximum nominal size of 20 mm was used as coarse aggregate. The properties were determined through:

a) Gradation Analysis: SNI 03-1968-1990
b) Specific Gravity and Water Absorption: SNI 1969-2008
c) Bulk Density: SNI 1973-2016
d) Moisture Content: SNI 03-1971-1990
e) Mud Content: SNI 03-4142-1996
f) Abrasion Resistance: SNI 03-2417-1991

3. Fine Aggregates

Natural river sand was used as fine aggregate, with the following tests performed:

a) Gradation Analysis: SNI 03-1968-1990
b) Specific Gravity and Water Absorption: SNI 1970-2008
c) Bulk Density: SNI 1973-2016
d) Moisture Content: SNI 03-1971-1990
e) Mud Content: SNI 03-4428-1997

4. Limestone Powder (LP)

Commercially available finely ground LP was used as a partial cement replacement at levels of 0%, 6%, 9%, 12%, and 15% by weight of cement. The replacement percentages were selected to evaluate the gradual effect of LP content on the fresh and hardened properties of SCC. The LP was characterized through: Bulk Density: SNI 1973-2016

5. Superplasticizer

Sikacim® Concrete Additive was used as a high-range water-reducing admixture at a fixed dosage of 2% by weight of cement in all mixtures to maintain the desired workability.

Concrete Mix Design

The SCC mix proportions were designed according to SNI 7656-2012 guidelines for normal, heavy, and mass concrete. Five mix variations were prepared corresponding to LP replacement levels of 0%, 6%, 9%, 12%, and 15% by weight of cement. The material proportions for each mixture were expressed in kg/m³. Water-to-binder ratios and superplasticizer dosage were kept constants for all mixes to isolate the effect of LP content on compressive strength and fresh properties of SCC.

SCC Workability Tests

Although the main focus of this study is compressive strength, the fresh properties of SCC were verified to ensure compliance with SCC criteria:

a) Filling Ability: Slump flow test per EFNARC guidelines, and SNI 1972:2008, with target spread diameter of 600–800 mm.
b) Passing Ability: L-Box test according to EFNARC guidelines with a blocking ratio (H_2/H_1) between 0.8 and 1.0.
c) Segregation Resistance: V-Funnel test according to EFNARC guidelines with target flow time between 6–12 seconds.
d) These tests ensured that all mixtures satisfied the requirements for SCC before compressive strength testing.

Specimen Preparation and Curing

Cube specimens with dimensions 150 mm × 150 mm × 150 mm were prepared for each LP variation by SNI 2493-2011. For each variation, five specimens were prepared for compressive strength testing at 28 days, resulting in a total of 25 specimens. After casting, the specimens were covered to prevent moisture loss and demolded after 24 hours. They were then cured in water at a temperature of 25 ± 2 °C until the designated testing age.

Compressive Strength Testing

Compressive strength tests were conducted at the age of 28 days according to SNI 03-1974-1990. The testing age of 28 days was selected because it represents the standard age for evaluating the design compressive strength of concrete. The maximum load applied by the compression testing machine was recorded, and compressive strength (f'c) was calculated using:

$$f'_c = \frac{P}{A}\mathrm{w} \qquad (1)$$

where f'_c is compressive strength (MPa), P is maximum load indicated by the testing machine (N), and A is cross-sectional area of the specimen (mm^2)

Data Analysis

The compressive strength results for each LP percentage were statistically analyzed to determine the effect of partial cement replacement with LP on SCC performance. The fresh property test results were also analyzed to evaluate the influence of LP content on SCC workability characteristics. Analysis focused on identifying the LP replacement level that maintains or improves compressive strength compared to the control mix (0% LP) .while still satisfying SCC fresh property requirements.

RESULTS AND DISCUSSIONS

The results in **Table 1** demonstrate that coarse aggregates exhibit generally higher specific gravity values compared to fine aggregates, with apparent specific gravity recorded at 2.59 and 2.48, respectively. Absorption was also slightly higher in coarse aggregates (2.45%) than fine aggregates (2.05%), indicating a higher water retention capacity, which may affect the effective water–cement ratio. The fineness modulus reflects expected particle size distribution differences, with coarse aggregates at 7.77 and fine aggregates at 2.39, confirming their complementary roles in concrete mix design. Bulk density values (1.47 kg/cm³ for coarse and 1.21 kg/cm³ for fine aggregates) also underline the importance of considering particle packing and void content to achieve optimum workability and strength. Similar findings were reported by Neville (2011), who emphasized the significance of specific gravity and bulk density in determining aggregate suitability for high-performance concrete.

In terms of quality indicators, the moisture content (0.85% for coarse and 0.95% for fine aggregates) and silt content (0.23% and 0.99%, respectively) were found to be within acceptable limits for concrete production, reducing the risk of weak interfacial bonding. The abrasion value of 5.42% for coarse aggregates highlights their good resistance to mechanical wear, supporting long-term durability in structural applications. These results are consistent with recent studies, such as Chinnu et al. (2021) in [19] reported that lower silt content and higher abrasion resistance of aggregates significantly improve the compressive strength and durability of self-compacting concrete. However, the relatively higher silt and moisture content in fine aggregates could increase water demand, potentially affecting workability and cement paste bonding, as also noted by Kostiunina et al. (2023) in [20]. Thus, proper control of the water-to-cement ratio and, if necessary, pre-treatment of fine aggregates is crucial. Future studies could expand on this by linking aggregate microstructure with durability properties under aggressive environmental conditions, as suggested by Sosa et al. (2021) in [21], providing a bridge between laboratory characterization and field performance.

Table 1. Aggregate Test Results.

No.	Test	Coarse Aggregates	Fine Aggregates	Unit
1	Apparent Specific Gravity	2.59	2.48	-
2	Bulk Specific Gravity (SSD Basic)	2.65	2.54	-
3	Bulk Specific Gravity (On Dry Basis)	2.76	2.62	-
4	Absorption	2.45	2.05	%
5	Fineness Modulus	7.77	2.39	-
6	Bulk Density	1,47	1,21	Kg/cm³
7	Moisture Content	0.85	0.95	%
8	Silt Content	0.23	0.99	%
9	Abrasion	5.42	-	%

The concrete mix was designed with a target slump of 75–100 mm, a compressive strength of 25 MPa, and a maximum aggregate size of 19 mm, supported by a planned standard deviation of 4.2, which reflects good quality control. The proportioning uses cement as the reference unit (1.000), with water at 0.598 to maintain adequate workability, fine aggregate at 1.163 to enhance packing and surface finish, and coarse aggregate at 2.264 to form the main load-bearing skeleton of the mix. This combination aims to ensure an optimum balance between strength, durability, and workability, which is critical for achieving structural-grade concrete in line with international guidelines

Table 2 illustrates the material weights for five cube test specimens with varying LP replacement levels. Cement is progressively replaced with LP at 6%, 9%, 12%, and 15%, reducing cement content from 8.4 kg to 6.3 kg while keeping water (4.25 kg), superplasticizer (0.2 kg), coarse aggregate (19.5 kg), and fine aggregate (12.1 kg) constant. This systematic variation enables a focused evaluation of LP’s influence on compressive strength. Previous studies have shown that moderate LP substitution (up to 15%) can improve particle packing density and accelerate early-age hydration, thereby enhancing strength development [6]. However, excessive LP may dilute clinker phases, reducing long-term strength due to lower calcium silicate hydrate (C-S-H) formation [22]. Thus, the present experimental design contributes to the ongoing debate by isolating LP’s role in modifying the mechanical behavior of self-compacting concrete, particularly in terms of compressive strength performance.

Table 2. Material weight for the five cube test specimens for each LP mixture variation

No	Variation (%)	Water (kg)	Superplasticizer (kg)	Cement (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Limestone Powder (kg)
1	0	4.25	0.2	8.4	19.5	12.1	0
2	6	4.25	0.2	7.9	19.5	12.1	0.5
3	9	4.25	0.2	6.74	19.5	12.1	0.8
4	12	4.25	0.2	6.52	19.5	12.1	1.0
5	15	4.25	0.2	6.30	19.5	12.1	1.3

Figure 1 presents the fresh properties of SCC with LP replacement levels. The flow table test values range from 610 mm (control) to 558 mm (15% LP), all of which are below the EFNARC (2005) recommended range of 600–850 mm at higher substitution levels. This indicates a reduction in flowability as LP content increases, likely due to the higher surface area and water demand of fine limestone particles. V-funnel results (8.12–9.22 s) remain within the specification limit of 8–12 s, showing acceptable viscosity across all mixes. L-box results, however, reveal a significant decline in passing ability at higher LP levels, dropping from 0.83 (control) to 0.47 (15% LP), with values below the acceptable range of 0.8–1.0, suggesting potential risk of blocking when LP content exceeds 9%.

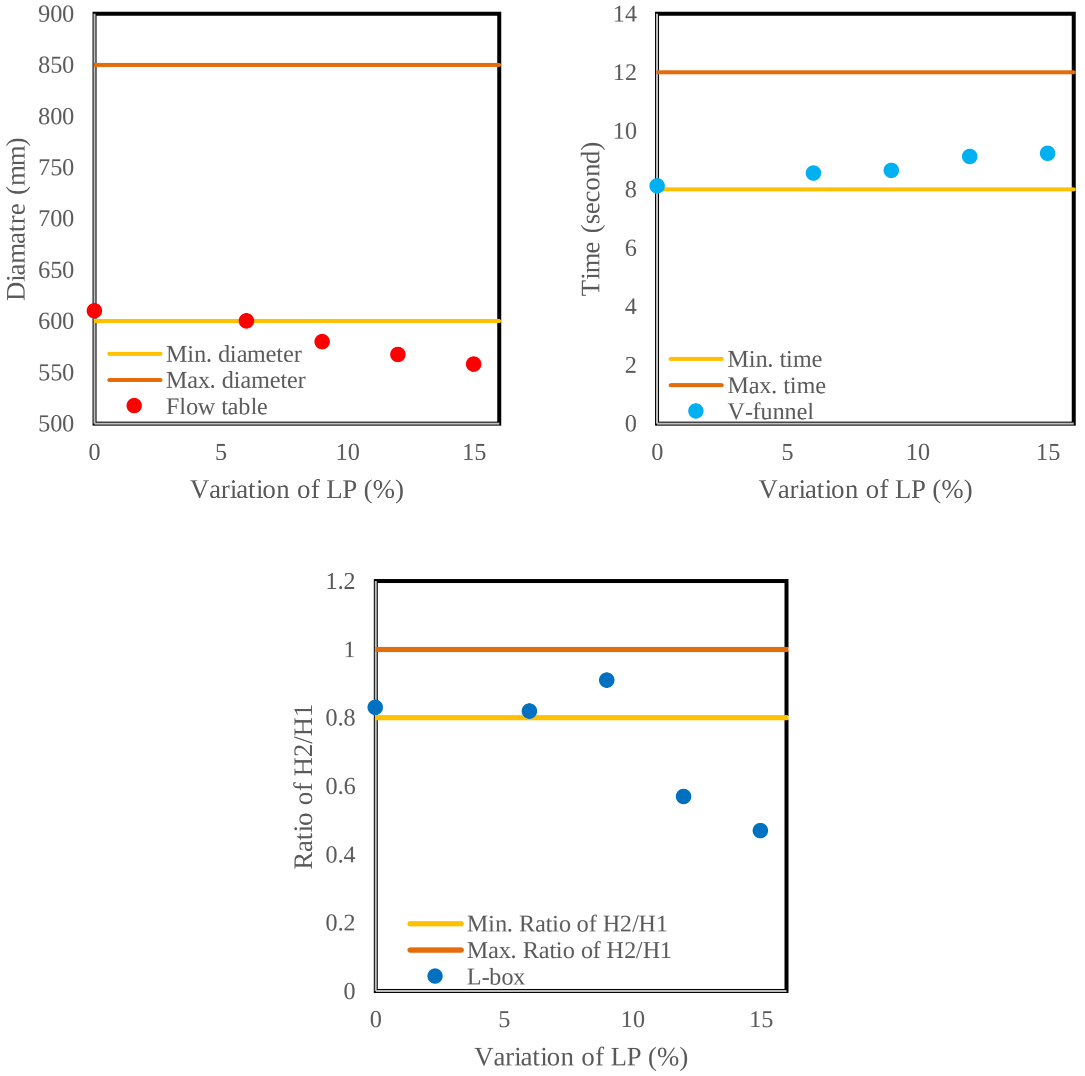

Figure 1. SCC concrete characteristic test results

These results highlight a critical trade-off in SCC design with LP substitution. While moderate LP replacement (≤ 9%) maintains satisfactory filling and passing abilities, excessive substitution (≥ 12%) adversely affects flowability and segregation resistance, reducing SCC performance. Previous studies similarly reported that LP enhances packing density and stability at low dosages, but higher levels compromise workability due to increased paste cohesiveness and reduced lubrication between aggregates [23]. Scientifically, this implies that LP is best used as a partial replacement to balance sustainability benefits (lower cement usage) without sacrificing fresh properties. Practically, the findings suggest limiting LP content in SCC to less than 10% to ensure compliance with EFNARC guidelines. Future studies may explore combining LP with supplementary cementitious materials (e.g., fly ash, silica fume) to offset the loss in workability at higher replacement levels.

Table 3 shows the effect of LP substitution on the compressive strength of concrete. The average compressive strength of the control mix (0% LP) was 27.14 MPa, exceeding the designed strength of 25 MPa. At 6% LP, the strength increased to 29.58 MPa, indicating that moderate LP replacement enhanced packing density and cement hydration, likely due to the filler and nucleation effects of fine limestone particles. However, higher LP contents (≥ 9%) resulted in a decline in strength, with values dropping to 24.34 MPa (12% LP) and 23.97 MPa (15% LP). This reduction was also reflected in the characteristic compressive strength, which fell well below the design target at higher substitution levels.

These findings suggest an optimal LP replacement level around 6%, where compressive strength was maximized due to improved microstructure and reduced porosity, consistent with prior research [23]. At higher LP percentages, the dilution of cementitious material likely outweighed the benefits of the filler, reducing hydration products and matrix cohesion. Scientifically, this aligns with the "filler-dilution balance" observed in limestone-modified systems, where only partial substitution is beneficial. Practically, the results indicate that LP can serve as a sustainable and cost-effective cement replacement. Still, its use should be limited to ≤ 6% to achieve structural-grade concrete meeting design strength. Future research could explore synergistic blends with supplementary cementitious materials to offset the strength loss at higher LP contents.

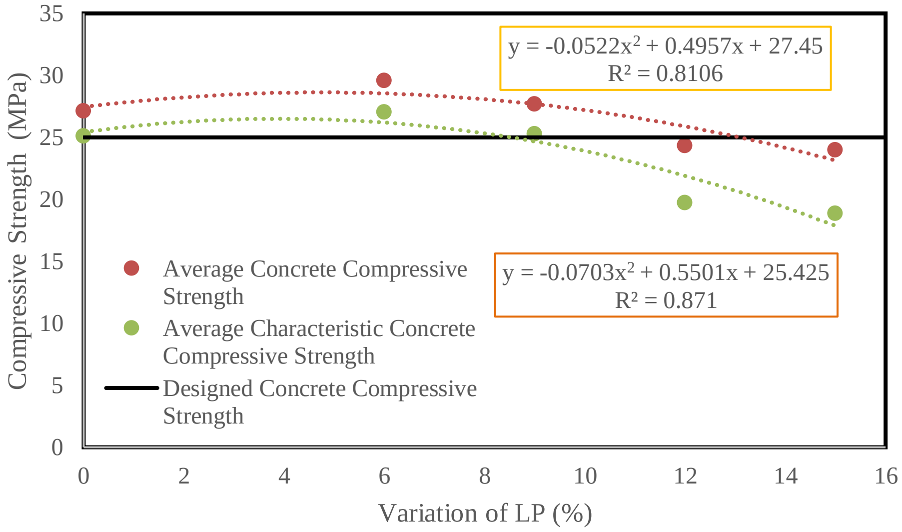

Figure 2. Concrete Compressive Strength Test Results

The evaluation of fresh properties in **Figure 1** shows that only the mixes with 0%, 6%, and 9% LP substitution meet the EFNARC criteria for SCC. These variations achieved adequate flowability (≥600 mm), acceptable V-funnel times (8–12 s), and L-box ratios within 0.8–1.0, confirming their ability to pass through reinforcement without segregation. In contrast, the 12% and 15% substitutions fell below the minimum flow table value and exhibited poor passing ability in the L-box test, thereby disqualifying them as SCC. This finding is consistent with studies such as [24], which emphasizes that excessive filler content can reduce flowability and hinder passing ability due to increased particle packing and viscosity.

Table 3. Concrete Compressive Strength Test Results

Result of Test	Variation (%)				
	0	6	9	12	15
Average Concrete Weight (kg)	7.78	8.09	8.1	7.62	7.54
Average Concrete Compressive Strength (MPa)	27.14	29.58	27.68	24.34	23.97
Average Characteristic Concrete Compressive Strength (MPa)	25.11	27.05	25.26	19.75	18.89
Designed Concrete Compressive Strength (MPa)			25		

When considering mechanical performance (**Table 4**), the same three mixes (0%, 6%, and 9%) not only satisfied SCC criteria but also met or exceeded the design compressive strength of 25 MPa. Among them, the 6% substitution yielded the highest compressive strength (29.58 MPa), suggesting an optimal balance between packing density and binder efficiency. Conversely, the 12% and 15% mixes fell below both the SCC requirements and the target strength, highlighting the detrimental effect of excessive LP replacement on workability and strength. These results underline that moderate LP substitution (up to 9%) can enhance SCC quality, while higher levels compromise both fresh and hardened properties. This aligns with findings by Elyamany et al. (2014) in [25] that optimal filler content improves SCC, but overdosage reduces its structural reliability.

CONCLUSION

This study demonstrated that incorporating LP as a partial cement replacement in SCC significantly influences both fresh and hardened properties. The experimental results confirmed that up to 9% substitution of LP can produce SCC that meets EFNARC standards for flowability, viscosity, and passing ability. At the same time, these mixes achieved compressive strengths that not only satisfied but, in some cases, exceeded the designed target of 25 MPa, with the 6% variation yielding the highest performance. These findings highlight that moderate LP inclusion can optimize the balance between workability and mechanical strength, contributing to more sustainable SCC by reducing cement consumption. However, higher LP replacement levels, particularly at 12% and 15%, resulted in decreased workability and compressive strength due to the dilution effect and reduced cementitious content in the mixture.

The theoretical contribution of this study lies in clarifying the performance threshold of LP in SCC and confirming that excessive substitution compromises the material's rheological stability and structural strength. Practically, the study provides engineers and practitioners with evidence-based guidance on the optimal dosage of LP in SCC mixtures, supporting both economic efficiency and environmental sustainability. Overall, the findings advance knowledge on the synergistic role of fine fillers in SCC technology, particularly in balancing fresh and hardened properties for reliable structural applications. The results also emphasize that excessive LP incorporation may negatively affect SCC performance, making careful dosage control essential in practical applications.

Future research should examine the microstructural mechanisms of LP interaction with cement paste and its influence on durability under aggressive environments. Techniques such as SEM and XRD could provide deeper insights into hydration and pore structure. For practice, LP can be safely applied in SCC at moderate levels to achieve sustainable, cost-effective concrete. Industry guidelines should integrate such substitution strategies, especially in regions with abundant limestone resources. Further studies could also combine LP with other supplementary cementitious materials to enhance both performance and sustainability.

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