Egypt. J. Chem. **Vol. 68,** SI: Z. M. Nofal, pp. 323- 338 (2025)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Mechanical Properties of Self-Compacted Lightweight Concrete Using LECA with Various Mineral Additives

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Abstract

This comprehensive study investigates the mechanical properties of self-compacted lightweight concrete (LW-SCC) manufactured with Light Expanded Clay Aggregate (LECA) and modified with various mineral additives including lime powder (LP), marble dust (MD), fly ash (FA), and granulated quartz (GQ) at different percentages (10%, 20%, and 30% by weight of cementitious materials). Fourteen concrete mixtures were prepared and evaluated for both fresh and hardened properties. Fresh properties were assessed through flow diameter, T500, J-ring, L-box, and V-funnel tests, while hardened properties including density, compressive strength, splitting tensile strength, flexural strength, and bond strength were determined at 7, 28, and 56 days. Results demonstrate significant improvements in mechanical properties with the incorporation of mineral additives. LECA concrete containing 10% lime powder exhibited 25% higher compressive strength than the control mix with silica fume. Marble dust at 20% provided optimal mechanical performance with a 35% increase in compressive strength and a 37% improvement in tensile strength. Fly ash showed progressive enhancement in mechanical properties with increasing content, achieving a 15% improvement in compressive strength at 30% replacement. Granulated quartz was most effective at 10% content, delivering 20% higher compressive strength and the highest bond strength improvement of 52.63% at 7 days. All mixtures maintained lightweight characteristics with densities between 1.70-1.75 t/m³. Fresh concrete properties improved with increasing mineral additive content, with enhanced flowability and passing ability. This research establishes that LECA can effectively produce structural lightweight self-compacted concrete with significantly enhanced mechanical properties through the strategic incorporation of mineral additives, offering promising applications in sustainable construction.

Keywords: Self-compacted lightweight concrete, Light Expanded Clay Aggregate (LECA), mineral additives, marble dust, fly ash, lime powder, granulated quartz, sustainable construction materials.

1. Introduction

Concrete is the most widely used construction material worldwide, with an annual global production exceeding 10 billion tons. The concrete industry contributes approximately 8% of global CO_2 emissions, primarily due to cement production, which has spurred intensive research efforts to develop more sustainable concrete formulations. Two significant advancements in concrete technology that address sustainability challenges are self-compacting concrete (SCC) and lightweight concrete (LWC) [1-3].

Lightweight concrete has gained significant attention in modern construction due to its advantages over conventional concrete. According to ACI Committee 213, lightweight concrete can be categorized into three types based on its application: insulating concrete (150-800 kg/m³), moderate-strength concrete (800-1400 kg/m³), and structural lightweight concrete (1400-2000 kg/m³). Among these, structural lightweight concrete has attracted considerable research interest due to its potential to reduce structural weight while maintaining adequate strength for load-bearing applications. The reduced dead load results in smaller structural elements, reduced foundation size, and lower seismic loads, thereby enabling more economical design. Additionally, lightweight concrete provides superior thermal and acoustic insulation properties, contributing to energy efficiency in buildings [4-6].

The mechanical properties of lightweight concrete produced with oil palm shell aggregates and concluded that proper mix design could achieve compressive strengths exceeding 30 MPa with densities below 1900 kg/m³ [7].

The reduced density of lightweight concrete offers several advantages in construction. such as a 25% reduction in concrete density could result in up to 20% savings in reinforcement requirements and foundation costs. Additionally, enhancement in thermal insulation properties of lightweight concrete, thermal conductivity values 40-50% lower than conventional concrete, which contributes to energy efficiency in buildings [8-9].

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Received date 23 March 2025; Revised date 12 April 2025; Accepted date 15 May 2025

DOI: 10.21608/EJCHEM.2025.369826.11502

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Self-compacting concrete (SCC) was first developed in Japan in the late 1980s as a solution to durability issues arising from inadequate compaction of conventional concrete. SCC defined as a highly flowable concrete that can spread readily into place, fill formwork, and encapsulate reinforcement without external compaction and without undergoing significant segregation or bleeding [10]. Self-compacting concrete represents a revolutionary development in concrete technology, characterized by its ability to flow under its weight, fill formwork, and achieve thorough compaction without external vibration, even in congested reinforcement areas. This technology offers numerous advantages including reduced construction time, labor costs, noise pollution, and improved surface finish, while enhancing durability through better consolidation [11-12]. Three principal methods for achieving self-compactability: increasing powder content, incorporating viscosity-modifying admixtures, or combining both approaches [13]. Several researchers have investigated the effects of various materials on SCC properties. Such as the influence of powder content on the fresh properties of SCC and reported that increasing the powder content improved the stability of the mixture but could adversely affect flowability if excessive. Also, the effects of various supplementary cementitious materials on SCC performance and found that their incorporation could enhance both fresh and hardened properties when properly proportioned [14-15].

The integration of lightweight aggregate technology with self-compacting concrete principles presents unique challenges due to the conflicting requirements of low density and high flowability without segregation.
The properties of self-compacting lightweight concrete made with pumice aggregate that achieving self-compactability required higher paste volume and careful adjustment of superplasticizer dosage compared to normal-weight SCC. A significant challenge in producing lightweight self-compacting concrete is preventing the segregation and floating of lightweight aggregates. By pre-soaking lightweight aggregates to reduce their initial absorption and by incorporating viscosity-modifying admixtures to enhance the stability of the fresh mixture. the use of silica fume in lightweight self-compacting concrete could significantly improve its stability and mechanical properties due to the high specific surface area and pozzolanic activity of silica fume particles [16-18].

Light Expanded Clay Aggregate (LECA), produced by heating clay to high temperatures (1100-1200°C) causing it to expand, has emerged as a promising lightweight aggregate for concrete production. LECA's cellular structure, characterized by numerous closed pores, results in low particle density (typically 0.3-0.9 g/cm³) while maintaining adequate strength. However, the inherent porosity of LECA introduces challenges in achieving optimal mechanical properties in concrete, particularly when self-compactability is also required [19-20].
Several researchers have investigated the performance of LECA in concrete, and reported that LECA-based concrete could achieve compressive strengths up to 35 MPa with densities around 1800 kg/m³, making it suitable for structural applications. Additionally, the enhancement of the thermal insulation properties of LECA concrete, with thermal conductivity values approximately 50% lower than conventional concrete. However, the incorporation of LECA in concrete introduces several challenges. The high water absorption and decrease of aggregate strength as significant factors affecting the mechanical properties and durability of LECA concrete. The pre-soaking or pre-wetting of LECA before mixing to minimize its effect on concrete workability and ensure adequate curing to optimize strength development[21-23].

Mineral additives, including supplementary cementitious materials and inert fillers, have been widely used to modify and enhance concrete properties. These materials can influence concrete through various mechanisms including filler effects, pozzolanic reactions, and by providing nucleation sites for cement hydration products. Lime powder, primarily consisting of calcium carbonate, acts predominantly as a filler in concrete.The incorporation of supplementary cementitious materials and mineral additives represents a potential strategy to enhance the mechanical properties of LECA-based self-compacted lightweight concrete. These materials can modify the microstructure, improve particle packing, and contribute to strength development through various mechanisms including filler effects, pozzolanic reactions, and nucleation sites for cement hydration products [24-28]. Limestone powder could enhance the early-age properties of concrete by accelerating cement hydration and improving particle packing [29]. The incorporation of limestone powder at 10-15% replacement levels could maintain or even improve the mechanical properties of concrete while reducing the cement content [30]. Marble dust, a by-product of marble cutting and shaping processes, has gained attention as a potential concrete additive. The effects of marble powder on concrete properties and found that it could enhance workability and mechanical properties when used as a partial replacement for cement up to certain proportions [31]. Compressive strength, split tensile strength, and flexural strength improved with 7.5% marble powder replacement, attributed to improved particle packing and enhanced hydration [32]. Fly ash, a by-product of coal combustion is one of the most widely used supplementary cementitious materials in concrete. Fly ash contributes to concrete properties through both physical (filler effect) and chemical (pozzolanic reaction) mechanisms. The pozzolanic reaction between fly ash and calcium hydroxide produced during cement hydration generates additional calcium silicate hydrate (C-S-H), which enhances long-term strength and durability. The fly ash typically reduces early-age strength but improves long-term mechanical properties and durability when used at replacement levels of 20-30% [33-34]. Granulated quartz, also known as silica flour, consists of finely ground high-purity quartz. The effects of silica flour on cement hydration and reported that it primarily acts as a filler and provides nucleation sites for hydration products, thereby accelerating early hydration, incorporation of fine quartz particles could enhance the microstructure of concrete through improved particle packing, particularly in mixtures with a high water-to-cement ratio [35-36].

Despite the potential benefits, the combined use of LECA and various mineral additives in self-compacting lightweight concrete remains inadequately investigated. The effects of different mineral additives on the fresh and hardened properties of LECA-based self-compacting lightweight concrete, their optimal proportions, and underlying enhancement mechanisms require a comprehensive assessment to enable their effective application in construction. This research aims to systematically evaluate the mechanical properties of self-compacted lightweight concrete manufactured with LECA and modified with four distinct mineral additives—lime powder, marble dust, fly ash, and granulated quartz—at varying proportions (10%, 20%, and 30% by weight of cementitious materials). The study encompasses a comprehensive assessment of both fresh properties, which determine the self-compactability characteristics, and hardened properties, which govern the structural performance. The findings provide valuable insights for developing optimized LECA-based self-compacted lightweight concrete formulations with enhanced mechanical performance, thereby contributing to sustainable construction practices.

2. Materials and Experimental Program

2.1. Materials

a) Cement and Silica Fume

Ordinary Portland cement (CEM I 42.5N) conforming to BS EN 197-1 was used as the primary binder in all concrete mixtures. The cement had a specific gravity of 3.15, an initial setting time of 150 minutes, and a final setting time of 220 minutes. The fineness of the cement was 2.8%, with a compressive strength of 19.56 MPa at 2 days and 44.8 MPa at 28 days, according to tests conducted as per E.S 2421-7/2006.

Silica fume with a specific gravity of 2.2 and a maximum fineness of 0.9% (percentage retained on sieve No. 325) was incorporated at 10% replacement of cement by weight to enhance the cohesiveness and strength of the lightweight self-compacted concrete. The chemical composition of the silica fume included a sulfate content (SO_3) of 0.428% and a chloride content of 0.3%.

Table 1. Properties of the cement used in the study.

Test description	Test results	E.S. (Specification limits)
Specific gravity	3.15	-
Percentage of water to give a paste of standard consistency w/c %	26%	-
Setting time (Vicat test) - Initial	150 min	Not less than 60 min (E.S 2421-1/2005)
Setting time (Vicat test) - Final	220 min	Not more than 10 hr. (E.S 2421-1/2005)
Fineness of cement	2.8%	Not more than 10%
Compressive strength - 2 days	19.56 N/mm²	Not less than 10 N/mm² (E.S 2421-7/2006)
Compressive strength - 28 days	44.8 N/mm²	(42.5-62.5) N/mm² (E.S 2421-7/2006)
Size stability (mm)	1.4 mm	Not more than 10 mm (E.S 2421-1/2005)
Loss of burning	3.75%	Not more than 5% (E.S 5325/2006)
Insoluble substances	3.55%	Not more than 5% (E.S 5325/2006)
Sulfate content (SO_3)	1.43%	Not more than 3.5% (E.S 5325/2006)
Chloride content	0.0212	Not more than 0.1% (E.S 5325/2006)

Table 2. Properties of silica fume used in the study.

Test description	**Test results**	**E.S. (Specification limits)**
Physical state	powder	-
Appearance (color)	grey	-
Density of Silica Fume	0.65	-
Specific gravity	2.2	-
Fineness of Silica Fume: Percent remained on sieve No. 325%	0.9%	not more than 10% according to ASTM C1240 – 2005
Loss on ignition (L.O.I%)	1.75%	not more than 6.0%
Insoluble residue (I.R %)	2.7%	-
Sulphates content %	0.428%	-
Total Chloride Ion Content	0.3%	-

b) Aggregates

Natural siliceous sand from Sohag quarries, El-Gurizat area, was used as fine aggregate. The sand had a specific gravity of 2.68, a fineness modulus of 3.012, and a bulk density of 1.72 t/m³. The chloride content of the sand was 0.042%, and the sulfate content (SO_3) was 0.21%.

Light Expanded Clay Aggregate (LECA) was used as the lightweight coarse aggregate. LECA was obtained from the National Cement Company (NCC) and had a bulk density of 0.89 t/m³, a specific gravity of 0.99, and a water absorption capacity of 18.64%. The LECA particles had a rounded shape with a diameter ranging from 4 to 15 mm, characterized by a porous interior structure and a dense exterior shell.

Table 3. Properties of the fine and coarse aggregate used in the study.

Test description	LECA	Sand
Volume weight	**0.89 t/m³**	**1.72 t/m³**
Specific gravity	**0.99**	**2.68**
Fineness modulus	**---**	**3.012**
The ratio of soft materials	**1.0%**	**0.1%**
Chloride content	**0.02%**	**0.042%**
Sulfate content (SO_3)	**0.073%**	**0.21%**
Organic impurities	**Nothing**	**Nothing**
Absorption%	**18.64%**	**---**

c) Mineral Additives

Four types of mineral additives were investigated in this study:

Lime Powder (LP): A by-product from limestone quarries in the El-Minya government, with a specific gravity of 2.7, a pH value of 8-9, and a fineness of 68% (percentage retained on sieve No. 325).

Marble Dust (MD): Obtained from the International Company for Mining and Investments (ICMI Company) in El-Sadat City, Menoufia government, Egypt. The marble dust had a specific gravity of 2.4, a pH value of 8-9, and a fineness of 44.8%.

Fly Ash (FA): Obtained from SIKA Company under the commercial name of Sika Fly Ash. The fly ash had a specific gravity of 2.13, a pH value of 8-9, and a fineness of 14%.

Granulated Quartz (GQ): Also known as ground silica, obtained from the ICMI Company. The granulated quartz had a specific gravity of 2.8, a pH value of 11, and a fineness of 1.0%.

Table 4. Properties of the mineral additives used in the study.

Test description	Ground Silica "GS"	Fly Ash "FA"	Marble Dust "MD"	Lime Powder "LP"
Physical state	Powder	Powder	Powder	Powder
Appearance	White	Grey	White	White
Fineness by using sieve no.325 (Percentage retained on the sieve)	1.0%	14%	44.8%	68%
PH	11	(8-9)	(8-9)	(8-9)
Specific gravity	2.8	2.13	2.4	2.7
Loss on ignition (L.O.I%)	1.01	5.34	36.02	45.11
Insoluble residue (IR%)	12.92	87.67	3.05	1.09
Sulfate content (SO_3)	1.6	1.94	1.16	1.6

d) Chemical Admixtures

A polycarboxylate-based high-range water-reducing admixture (SikaViscoCrete -3425) was used as a superplasticizer to achieve the required flowability for self-compactability. The admixture had a density of 1.087, a pH value of 4.64, and a solid content of 42.69%. It complied with the requirements for superplasticizers according to ASTM C-494 Types G and F, and BS EN 934 part 2: 2001.

e) Water

Clean drinking water, free from salt and impurities, was used for mixing and curing procedures. The water had a chloride content of 71 ppm (below the limit of 500 ppm), a sulfate content of 202.9 ppm (below the limit of 300 ppm), and a total dissolved solids content of 104 ppm (below the limit of 2000 ppm). The pH value of the water was 7.81, within the range of 6 to 8.5 as specified in IS 456: 2000.

2.2. Mix Design and Proportioning

In this study, a total of fourteen concrete mixtures were designed based on ACI 211.2-98 guidelines for lightweight concrete and modified to achieve self-compactability. The mixtures were designated as follows:

- LECA C0: Control mixture with 100% ordinary Portland cement (no silica fume or mineral additives).
- LECA C1: Control mixture with 90% ordinary Portland cement and 10% silica fume replacement.
- LECA LP10, LP20, LP30: Mixtures with 10% silica fume and lime powder at 10%, 20%, and 30% addition by weight of cementitious materials.
- LECA MD10, MD20, MD30: Mixtures with 10% silica fume and marble dust at 10%, 20%, and 30% addition by weight of cementitious materials.
- LECA FA10, FA20, FA30: Mixtures with 10% silica fume and fly ash at 10%, 20%, and 30% addition by weight of cementitious materials.
- LECA GQ10, GQ20, GQ30: Mixtures with 10% silica fume and granulated quartz at 10%, 20%, and 30% addition by weight of cementitious materials.

The mix proportions were designed to achieve adequate self-compactability and a target 28-day compressive strength exceeding 25 MPa. The water-to-cementitious materials ratio was adjusted based on the water demand of each mineral additive to maintain the required.

Table 5. The Proportion of concrete LECA mixes used in the current study.

Mix code	Components						Mineral additive		
	C (kg)	SF (kg)	W (kg)	F.A (kg)	C.A (kg)	Viscocrete (SP) (kg)	Type	Percentage %	Weight (kg)
LECA C0	500	---	170	721	373.8	7.5	--	--	--
LECA C1	450	50	170	721	373.8	7.5	--	--	--
LECA LP10	450	50	187	721	373.8	7.5	Lime powder	10	50
LECA LP20	450	50	204	721	373.8	7.5		20	100
LECA LP30	450	50	221	721	373.8	7.5		30	150
LECA MD10	450	50	187	721	373.8	7.5	Marble dust	10	50
LECA MD20	450	50	204	721	373.8	7.5		20	100
LECA MD30	450	50	221	721	373.8	7.5		30	150
LECA FA10	450	50	187	721	373.8	7.5	Fly ash	10	50
LECA FA20	450	50	204	721	373.8	7.5		20	100
LECA FA30	450	50	221	721	373.8	7.5		30	150
LECA GQ10	450	50	187	721	373.8	7.5	Granulated quartz	10	50
LECA GQ20	450	50	204	721	373.8	7.5		20	100
LECA GQ30	450	50	221	721	373.8	7.5		30	150

2.3. Specimen Preparation and Curing

The concrete mixing procedure was standardized for all mixtures to ensure consistency. The dry materials (cement, silica fume, mineral additives, sand, and LECA) were first mixed for approximately 2 minutes in a laboratory pan mixer. LECA was used in a pre-wetted surface-dry condition to minimize its effect on concrete workability. Water mixed with the superplasticizer was then gradually added while continuing the mixing process for an additional 3 minutes until a homogeneous mixture was achieved.

After assessing the fresh properties, the concrete was cast in various molds according to the requirements of different mechanical tests. The specimens were cast in a single layer without vibration, relying on the self-compactability of the mixtures. After casting, the specimens were covered with plastic sheets to prevent moisture loss and maintained at a temperature of 20 ± 2°C for 24 hours.

Following demolding at 24 hours, the specimens were subjected to water curing at 20 ± 2°C for the designated periods (7, 28, and 56 days) before testing. The specimens for each mechanical test were as follows:

- Compressive strength: Cubic specimens (150 × 150 × 150 mm), 9 cubes for each mixture.
- Splitting tensile strength: Cylindrical specimens (150 × 300 mm), 6 cylinders for each mixture.
- Flexural strength: Prismatic specimens (100 × 100 × 500 mm), 6 beams for each mixture.
- Bond strength: Cubic specimens (150 × 150 × 150 mm) with embedded reinforcement, 6 cubes for each mixture.

2.4. Testing Procedures

a) Fresh Concrete Properties

The fresh concrete properties were assessed through several tests according to the European Guidelines for Self-Compacting Concrete (EFNARC) and the Egyptian Code of Practice (ECP 203-2020):

- Flow Diameter Test (Slump Flow): This test evaluated the horizontal free flow (spread) of SCC in the absence of obstructions. The test was performed according to EFNARC guidelines, with the diameter of the concrete patty measured in two perpendicular directions after the slump cone was lifted. A flow diameter of 550-850 mm is typically required for SCC.
- T500 Test: This test measured the time taken for the concrete to reach a spread diameter of 500 mm from the moment the slump cone was lifted. The test was performed in conjunction with the flow diameter test and indicated the viscosity and filling ability of the mixture.
- J-Ring Test: This test assessed the passing ability of SCC through congested reinforcement. A J-Ring with vertical rods was placed around the slump cone, and the height difference between the concrete inside and outside the ring was measured after flow had ceased. A difference of less than 15 mm is typically required for good passing ability.
- L-Box Test: This test evaluated the passing ability of SCC in confined spaces. The test apparatus consisted of a vertical section and a horizontal section separated by a sliding gate with reinforcement bars. The ratio of the heights at the end and beginning of the horizontal section (H2/H1) was measured, with values above 0.8 indicating good passing ability.
- V-Funnel Test: This test assessed the viscosity and filling ability of SCC. The time taken for the concrete to flow through a V-shaped funnel was measured, with values between 6 and 12 seconds considered acceptable for SCC. The test was performed twice: immediately (T_0) and after 5 minutes (T_5), with the difference between the two measurements indicating the segregation resistance.

b) Hardened Concrete Properties

The hardened concrete properties were assessed through several tests according to the applicable standards:

- Density: The density of hardened concrete was determined according to BS EN 12390-7 by measuring the weight and volume of the cubic specimens before the compressive strength test.
- Compressive Strength: The compressive strength was determined according to BS EN 12390-3 using cubic specimens (150 × 150 × 150 mm) at ages 7, 28, and 56 days. The load was applied at a rate of 0.6 ± 0.2 MPa/s until failure, and the maximum load was recorded.
- Splitting Tensile Strength: The splitting tensile strength was determined according to BS EN 12390-6 using cylindrical specimens (150 × 300 mm) at ages 7, 28, and 56 days. The test involved applying a compressive load along the length of the cylinder until splitting failure occurred.
- Flexural Strength: The flexural strength was determined according to BS EN 12390-5 using prismatic specimens (100 × 100 × 500 mm) at ages 7, 28, and 56 days. The test was performed using a four-point loading arrangement, with the load applied at a rate of 0.05 ± 0.01 MPa/s until failure.
- Bond Strength: The bond strength between concrete and reinforcement was determined according to RILEM RC6 using cubic specimens (150 × 150 × 150 mm) with a centrally embedded reinforcement bar. The bond strength was calculated from the pull-out force required to cause bond failure, with the test performed at ages of 7, 28, and 56 days.

All mechanical tests were conducted using calibrated testing machines, and the results were reported as the average of at least three specimens for each test and age.

3. Results and discussion

3.1. Fresh Concrete Properties

The fresh concrete properties of all LECA concrete mixtures were assessed to evaluate their self-compactability characteristics. The results of the flow diameter test, T500 test, J-ring test, L-box test, and V-funnel test are presented in Table 6.

Table 6. The effect of using mineral additives with different ratios on the Flow diameter Test, T500 Test, J-Ring Test, L-Box Test, and V-Funnel Test of concrete mixes made by LECA.

Concrete Mixes				Fresh Concrete Tests					
Code of concrete mixes	The ratio of silica fume	Ratio of mineral additives	Type of mineral additives	Flow diameter Test (mm)	T 500 Test (sec)	J-Ring Test (mm)	L-Box Test (H2/H1)	V-Funnel Test T_0 (sec)	V-Funnel Test T_5 (sec)
LECA C0	0%	0%	NONE	600	5	20	0.91	12	15
LECA C1	10%	0%	NONE	600	5	18	0.95	10	13
LECA LP10	10%	10%	Lime - powder	600	5	16	0.875	10	13
LECA LP20	10%	20%		700	5	14	0.885	8	11
LECA LP30	10%	30%		700	5	10	0.937	6	9
LECA MD10	10%	10%	Marble – dust	650	5	16	0.9	12	15
LECA MD20	10%	20%		750	5	12	0.897	11	14
LECA MD30	10%	30%		750	5	10	0.891	10	13
LECA FA10	10%	10%	Fly-Ash	650	5	12	0.85	10	13
LECA FA20	10%	20%		700	4	10	0.925	9	12
LECA FA30	10%	30%		700	4	8	0.94	8	11
LECA GQ10	10%	10%	Granulated - Quartz	700	5	16	0.937	12	15
LECA GQ20	10%	20%		700	5	12	0.936	11	14
LECA GQ30	10%	30%		750	4	10	0.911	10	13

a) Flow Diameter and T500 Tests

The flow diameter test results showed that all LECA concrete mixtures achieved the minimum flow diameter of 550 mm required for self-compacting concrete according to EFNARC guidelines. The control mixtures (LECA C0 and LECA C1) exhibited identical flow diameters of 600 mm. The incorporation of mineral additives resulted in improved flowability, with the flow diameter increasing as the percentage of mineral additives increased.

The lime powder-containing mixtures showed flow diameters of 600 mm, 700 mm, and 700 mm for 10%, 20%, and 30% additional levels, respectively. This improvement in flowability with increasing lime powder content can be attributed to the "ball-bearing" effect of the fine lime particles, which reduces friction between aggregate particles and enhances the fluidity of the mixture.

The marble dust-containing mixtures demonstrated even greater improvement in flowability, with flow diameters of 650 mm, 750 mm, and 750 mm for 10%, 20%, and 30% addition levels, respectively. The smooth surface texture and low water absorption of marble dust particles contribute to this enhanced flowability by reducing water demand and improving particle dispersion.

The fly ash-containing mixtures exhibited flow diameters of 650 mm, 700 mm, and 700 mm for 10%, 20%, and 30% addition levels, respectively. The spherical shape of fly ash particles reduces internal friction and improves the rheological properties of the concrete, resulting in enhanced flowability.

The granulated quartz-containing mixtures showed flow diameters of 700 mm, 700 mm, and 750 mm for 10%, 20%, and 30% addition levels, respectively. The improved flowability can be attributed to the fine particle size and smooth surface texture of granulated quartz, which enhances particle packing and reduces water demand.

The T500 test results indicated that all mixtures achieved adequate viscosity for self-compacting concrete. The control mixtures and most mineral additive-containing mixtures exhibited T500 values of 5 seconds, while the high-content fly ash (20% and 30%) and high-content granulated quartz (30%) mixtures showed slightly reduced T500 values of 4 seconds. This reduction in T500 values indicates a decrease in viscosity, which can be attributed to the lubricating effect of fine spherical particles in these additives.

b) J-Ring Test

The J-ring test results revealed that all LECA concrete mixtures achieved adequate passing ability, with J-ring values below the maximum limit of 25 mm specified by EFNARC. The control mixtures (LECA C0 and LECA C1) exhibited J-ring values of 20 mm and 18 mm, respectively. The incorporation of mineral additives resulted in improved passing ability, with the J-ring value decreasing as the percentage of mineral additives increased.

The lime powder-containing mixtures showed J-ring values of 16 mm, 14 mm, and 10 mm for 10%, 20%, and 30% addition levels, respectively. The marble dust-containing mixtures exhibited J-ring values of 16 mm, 12 mm, and 10 mm for 10%, 20%, and 30% addition levels, respectively. The fly ash-containing mixtures demonstrated J-ring values of 12 mm, 10 mm, and 8 mm for 10%, 20%, and 30% addition levels, respectively. The granulated quartz-containing mixtures showed J-ring values of 16 mm, 12 mm, and 10 mm for 10%, 20%, and 30% addition levels, respectively.

The improvement in passing ability with increasing mineral additive content can be attributed to several factors: (1) the fine particles fill the spaces between larger particles, reducing interparticle friction; (2) the increased paste volume improves the lubrication of aggregate particles; and (3) the reduced likelihood of segregation and blocking around reinforcement.

c) L-Box Test

The L-box test results indicated that all LECA concrete mixtures achieved adequate passing ability in confined spaces. The H2/H1 ratio for all mixtures exceeded the minimum requirement of 0.8 specified by EFNARC, with values ranging from 0.85 to 0.95. The control mixtures (LECA C0 and LECA C1) exhibited H2/H1 ratios of 0.91 and 0.95, respectively.

The lime powder-containing mixtures showed H2/H1 ratios of 0.875, 0.885, and 0.937 for 10%, 20%, and 30% addition levels, respectively. The marble dust-containing mixtures exhibited H2/H1 ratios of 0.9, 0.897, and 0.891 for 10%, 20%, and 30% addition levels, respectively. The fly ash-containing mixtures demonstrated H2/H1 ratios of 0.85, 0.925, and 0.94 for 10%, 20%, and 30% addition levels, respectively. The granulated quartz-containing mixtures showed H2/H1 ratios of 0.937, 0.936, and 0.911 for 10%, 20%, and 30% addition levels, respectively.

The variation in H2/H1 ratios among different mixtures can be attributed to differences in viscosity and cohesiveness. While all mixtures achieved adequate passing ability, those with higher H2/H1 ratios exhibited better flow characteristics in confined spaces, which is advantageous for applications involving complex formwork geometries or congested reinforcement.

d) V-Funnel Test

The V-funnel test results showed that all LECA concrete mixtures achieved adequate filling ability and viscosity for self-compacting concrete. The T_0 values ranged from 6 to 12 seconds, within the acceptable range specified by EFNARC. The control mixtures (LECA C0 and LECA C1) exhibited T_0 values of 12 and 10 seconds, respectively.

The lime powder-containing mixtures showed T_0 values of 10, 8, and 6 seconds for 10%, 20%, and 30% addition levels, respectively. The marble dust-containing mixtures exhibited T_0 values of 12, 11, and 10 seconds for 10%, 20%, and 30% addition levels, respectively. The fly ash-containing mixtures demonstrated T_0 values of 10, 9, and 8 seconds for 10%, 20%, and 30% addition levels, respectively. The granulated quartz-containing mixtures showed T_0 values of 12, 11, and 10 seconds for 10%, 20%, and 30% addition levels, respectively.

The T_5 values for all mixtures ranged from 9 to 15 seconds, with the difference between T_5 and T_0 values less than 3 seconds, indicating adequate segregation resistance. The control mixtures (LECA C0 and LECA C1) exhibited T_5 values of 15 and 13 seconds, respectively. The lime powder-containing mixtures showed T_5 values of 13, 11, and 9 seconds for 10%, 20%, and 30% addition levels, respectively. The marble dust-containing mixtures exhibited T_5 values of 15, 14, and 13 seconds for 10%, 20%, and 30% addition levels, respectively. The fly ash-containing mixtures demonstrated T_5 values of 13, 12, and 11 seconds for 10%, 20%, and 30% addition levels, respectively. The granulated quartz-containing mixtures showed T_5 values of 15, 14, and 13 seconds for 10%, 20%, and 30% addition levels, respectively.

The decrease in both T_0 and T_5 values with increasing mineral additive content indicates a reduction in viscosity, which can be attributed to the improved particle packing and reduced water demand resulting from the incorporation of fine mineral particles. However, the small difference between T_5 and T_0 values for all mixtures suggests adequate cohesiveness and stability, preventing segregation and floating of lightweight aggregates.

3.2. Hardened Concrete Properties

a) Density

The density of hardened concrete was measured for all mixtures to verify their classification as lightweight concrete. The results are presented in Table 7 along with other mechanical properties.

Table 7. The effect of using mineral additives with different ratios on the Mechanical properties of the hardened concrete mixtures made by LECA.

Concrete Mixes				Mechanical properties of the hardened concrete mixtures 15*15 cm												
Code of concrete mixes	The ratio of silica fume	Ratio of mineral additives	Type of mineral additives	Density (t/m3)	Compressive Strength (MPa)			Tensile Strength (MPa)			Flexural Strength (MPa)			Bond Strength (MPa)		
					7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
Leca C0	0 %	0 %	NONE	1.75	18	23	25	2	2.4	2.5	2.5	3.3	4.2	16	22	24
Leca C1	10 %	0 %	NONE	1.75	20	25	27	2.1	2.5	2.6	2.8	3.6	4.6	19	24	26
Leca LP10	10 %	10 %	Lime - powder	1.72	25	30	31.5	2.7	3.2	3.3	4.3	5	5.5	26	31	33
Leca LP20	10 %	20 %		1.73	23	28	30	2.6	3	3.1	3.5	4.4	4.9	23	29	31
Leca LP30	10 %	30 %		1.72	21.5	25.5	27.5	2.4	2.8	2.9	3.1	3.9	4.8	22	27	29
Leca MD10	10 %	10 %	Marble – dust	1.70	22.5	28	30	2.4	2.8	2.9	3	3.8	4.8	23	28	30
Leca MD20	10 %	20 %		1.71	27	33.5	36	2.88	3.4	3.5	3.9	4.7	5.4	26	31	33.5
Leca MD30	10 %	30 %		1.75	25.6	31	33	2.3	2.6	2.7	2.9	3.7	4.7	22	27	29
Leca FA10	10 %	10 %	Fly-Ash	1.70	20	25	27	2.1	2.5	2.6	2.8	3.6	4.6	19	24	26
Leca FA20	10 %	20 %		1.73	21.5	26	28	2.2	2.6	2.7	2.9	3.7	4.7	21	26	28
Leca FA30	10 %	30 %		1.75	23	28	30	2.4	2.8	2.9	3	3.8	4.8	25	31.5	34
Leca GQ10	10 %	10 %	Granulated - Quartz	1.72	24	30	32.5	2.7	3.2	3.3	3.3	4.1	4.9	29	34	36
Leca GQ20	10 %	20 %		1.74	22	27.5	30	2.2	2.6	2.7	2.9	3.7	4.7	26	32	34
Leca GQ30	10 %	30 %		1.75	21	26	28	2.1	2.5	2.6	2.8	3.6	4.6	25	29	31

All mixtures exhibited densities within the range of 1.70 to 1.75 t/m³, well below the maximum limit of 2.0 t/m³ for lightweight concrete according to BS EN 206-1. This consistent achievement of lightweight characteristics across all mixtures confirms the effectiveness of LECA as a lightweight aggregate for structural applications.

The variation in density among different mixtures was minimal, with a maximum difference of only 0.05 t/m³. This marginal variation can be attributed to differences in the specific gravity of the various mineral additives and their effect on the microstructure of the concrete. The slightly lower densities observed for some mixtures (e.g., LECA MD10 and LECA FA10, both at 1.70 t/m³) can be attributed to the lower specific gravity of these additives and potentially increased air entrainment.

b) Compressive Strength

The compressive strength development of all LECA concrete mixtures at 7, 28, and 56 days is illustrated in Figure 1.

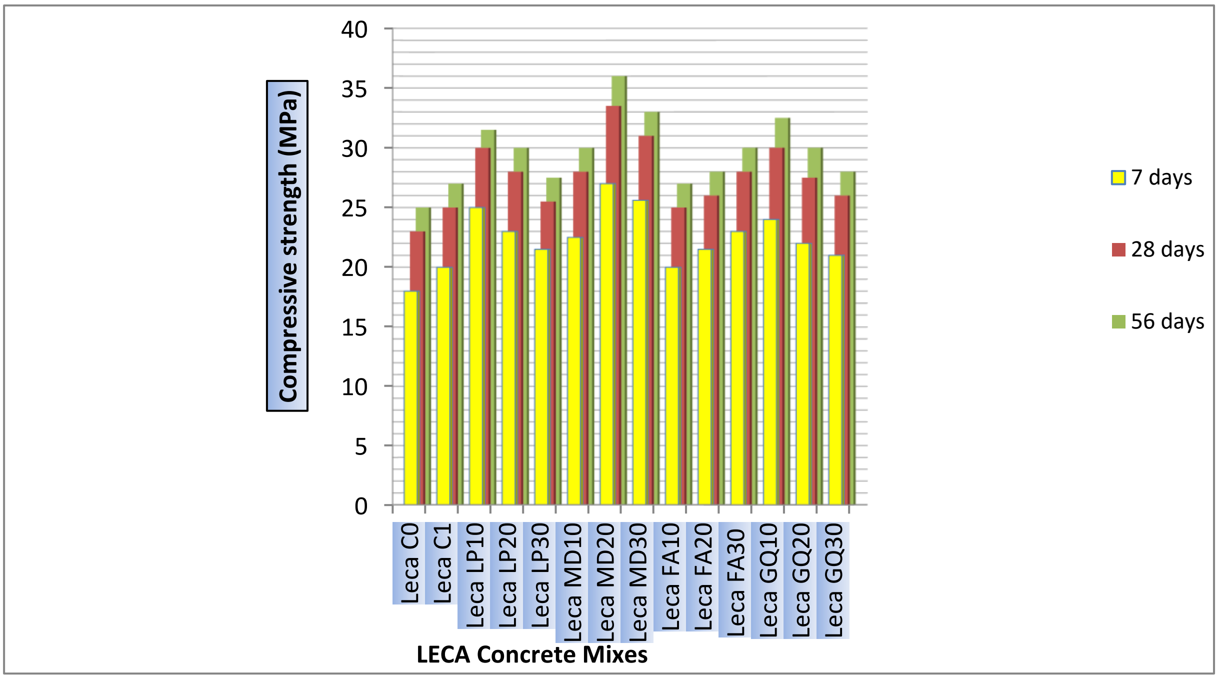

Figure 1: Compressive strength development of LECA concrete mixtures

The compressive strength results demonstrated that all LECA concrete mixtures achieved the minimum target strength of 25 MPa at 28 days, making them suitable for structural applications. The control mixtures (LECA C0 and LECA C1) showed compressive strengths of 23 MPa and 25 MPa at 28 days, respectively. The incorporation of silica fumes in LECA C1 resulted in an 8.7% increase in compressive strength compared to LECA C0, which can be attributed to the pozzolanic reaction and filler effect of silica fume particles.

The incorporation of mineral additives resulted in varied effects on compressive strength, dependent on both the type and percentage of the additive. The lime powder-containing mixtures exhibited compressive strengths of 30 MPa, 28 MPa, and 25.5 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The improvement in compressive strength with 10% lime powder (than LECA C1) can be attributed to several mechanisms:

- Accelerated Hydration: Fine lime particles provide nucleation sites for cement hydration products, accelerating the early hydration process.
- Improved Particle Packing: The fine particles of lime powder fill the interstitial spaces between cement particles, resulting in a denser microstructure.
- Formation of Carboaluminates: The reaction between calcium carbonate in lime powder and aluminate phases in cement can form carboaluminate hydrates, which contribute to strength development.

However, the decrease in compressive strength with increasing lime powder content beyond 10% suggests a dilution effect, where the beneficial mechanisms are outweighed by the reduction in cement content relative to total powder content.
The marble dust-containing mixtures demonstrated compressive strengths of 28 MPa, 33.5 MPa, and 31 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 20% marble dust mixture exhibited the highest compressive strength among all mixtures, with a 34% increase compared to LECA C1. This significant improvement can be attributed to:

- Optimized Particle Packing: The marble dust particles with intermediate fineness between cement and silica fume optimize the particle size distribution, resulting in enhanced particle packing and reduced porosity.
- Nucleation Effect: The fine marble dust particles serve as nucleation sites for cement hydration products, accelerating the hydration process.
- Calcium Carbonate Reaction: The calcium carbonate in marble dust can react with aluminate phases in cement to form carboaluminate hydrates, contributing to strength development.

The fly ash-containing mixtures showed compressive strengths of 25 MPa, 26 MPa, and 28 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. Unlike the other mineral additives, fly ash exhibited progressive improvement in compressive strength with increasing content, with the 30% fly ash mixture showing a 12% increase compared to LECA C1.

This trend can be explained by:

- Pozzolanic Reaction: Fly ash contains amorphous silica and alumina that react with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H), the primary strength-providing phase in concrete.
- Enhanced Long-Term Strength: The pozzolanic reaction of fly ash continues over an extended period, contributing to long-term strength development.
- Improved Microstructure: The spherical particles of fly ash improve particle packing and reduce water demand, resulting in a denser microstructure with reduced porosity.

The granulated quartz-containing mixtures exhibited compressive strengths of 30 MPa, 27.5 MPa, and 26 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% granulated quartz mixture showed a 20% increase in compressive strength compared to LECA C1. This improvement can be attributed to:

- Filler Effect: The extremely fine granulated quartz particles fill the interstitial spaces between cement particles, resulting in a denser microstructure with reduced porosity.
- Enhanced Nucleation: The high surface area of granulated quartz particles provides numerous nucleation sites for cement hydration products, accelerating the hydration process.
- Potential Pozzolanic Activity: Although granulated quartz is considered relatively inert, some studies suggest that finely ground quartz can exhibit limited pozzolanic activity, particularly in the presence of activators such as calcium hydroxide.

The compressive strength development over time followed a typical pattern for all mixtures, with substantial early strength gain between 7 and 28 days, followed by more modest increases between 28 and 56 days. However, the rate of strength development varied among different mixtures. The marble dust and granulated quartz mixtures exhibited relatively rapid early strength development, while the fly ash mixtures showed more gradual strength gain, with a higher proportion of the ultimate strength developed between 28 and 56 days.
The optimal percentage of each mineral additive for maximum compressive strength was 10% for lime powder, 20% for marble dust, 30% for fly ash, and 10% for granulated quartz. These findings provide valuable guidance for selecting the appropriate mineral additive type and proportion for specific strength requirements and construction schedules.

c)Splitting Tensile Strength
The splitting tensile strength results for all LECA concrete mixtures at 7, 28, and 56 days are presented in Figure 2.

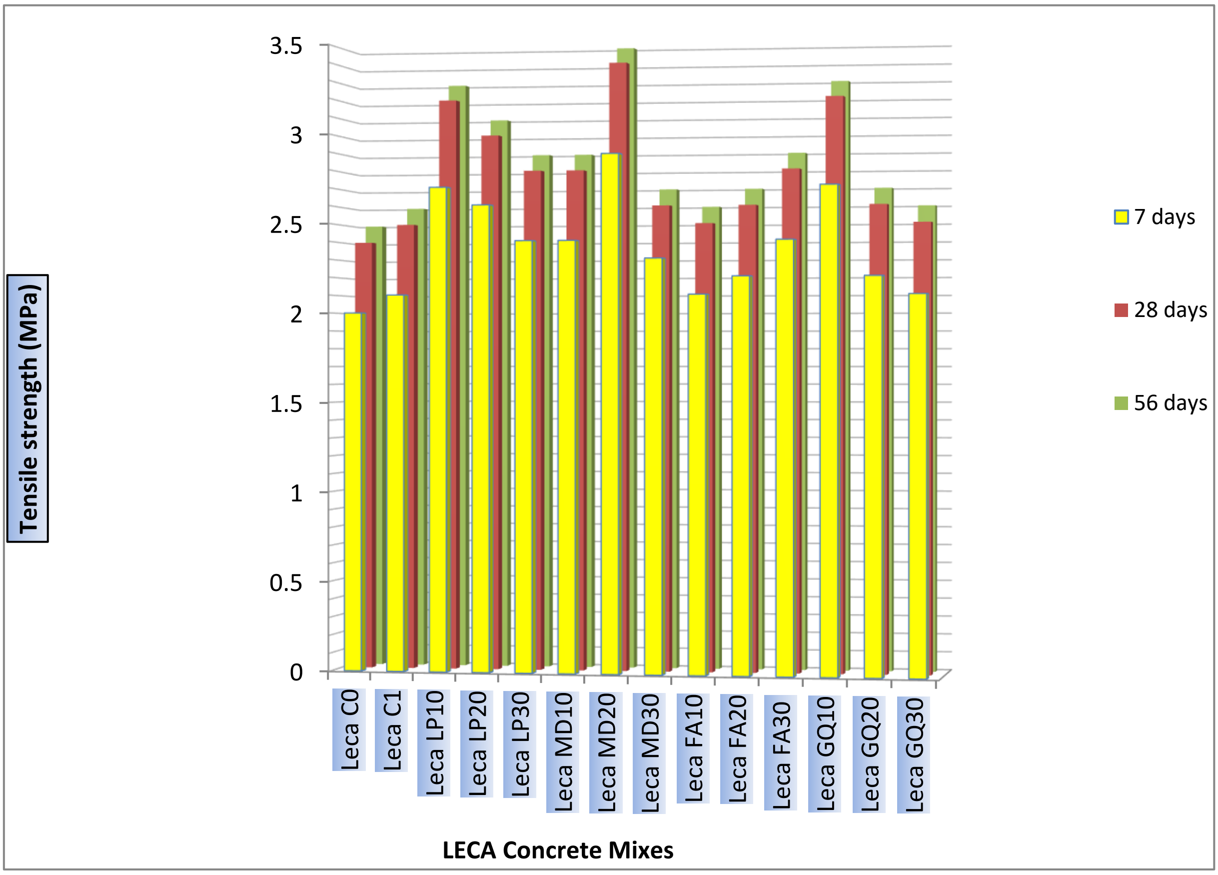

Figure 2: Splitting tensile strength of LECA concrete mixtures.

The splitting tensile strength results demonstrated trends similar to those observed for compressive strength, although with some variations. The control mixtures (LECA C0 and LECA C1) exhibited splitting tensile strengths of 2.4 MPa and 2.5 MPa at 28 days, respectively. The incorporation of mineral additives resulted in varied effects on tensile strength, dependent on both the type and percentage of the additive.

The lime powder-containing mixtures showed splitting tensile strengths of 3.2 MPa, 3.0 MPa, and 2.8 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% lime powder mixture exhibited a 28% improvement in tensile strength compared to LECA C1. This enhancement can be attributed to similar mechanisms as those for compressive strength, including improved particle packing, accelerated hydration, and the formation of additional binding phases. However, the decrease in tensile strength with increasing lime powder content suggests a threshold beyond which the beneficial effects are outweighed by the dilution of cement.

The marble dust-containing mixtures demonstrated splitting tensile strengths of 2.8 MPa, 3.4 MPa, and 2.6 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 20% marble dust mixture exhibited the highest tensile strength among all mixtures, with a 36% increase compared to LECA C1. This significant improvement can be attributed to the optimized particle packing, enhanced hydration kinetics, and potential formation of additional binding phases. The reduced tensile strength at 30% marble dust content suggests a threshold beyond which excessive replacement becomes detrimental.

The fly ash-containing mixtures showed splitting tensile strengths of 2.5 MPa, 2.6 MPa, and 2.8 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. Similar to the compressive strength results, fly ash exhibited progressive improvement in tensile strength with increasing content, with the 30% fly ash mixture showing a 12% increase compared to LECA C1. This trend can be explained by the pozzolanic reaction of fly ash, which contributes to long-term strength development through the formation of additional calcium silicate hydrate (C-S-H).

The granulated quartz-containing mixtures exhibited splitting tensile strengths of 3.2 MPa, 2.6 MPa, and 2.5 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% granulated quartz mixture showed a 28% increase in tensile strength compared to LECA C1. This improvement can be attributed to the filler effect and enhanced nucleation provided by the fine-granulated quartz particles. However, the reduction in tensile strength with increasing granulated quartz content suggests a threshold beyond which excessive replacement becomes detrimental.

The tensile-to-compressive strength ratio ranged from 0.09 to 0.11 for all mixtures, which is typical for lightweight concrete. This ratio is slightly lower than the 0.10 to 0.15 typically observed for normal-weight concrete, which can be attributed to the weaker aggregate-matrix interface in lightweight concrete.

d) Flexural Strength

The flexural strength results for all LECA concrete mixtures at 7, 28, and 56 days are presented in Figure 3.

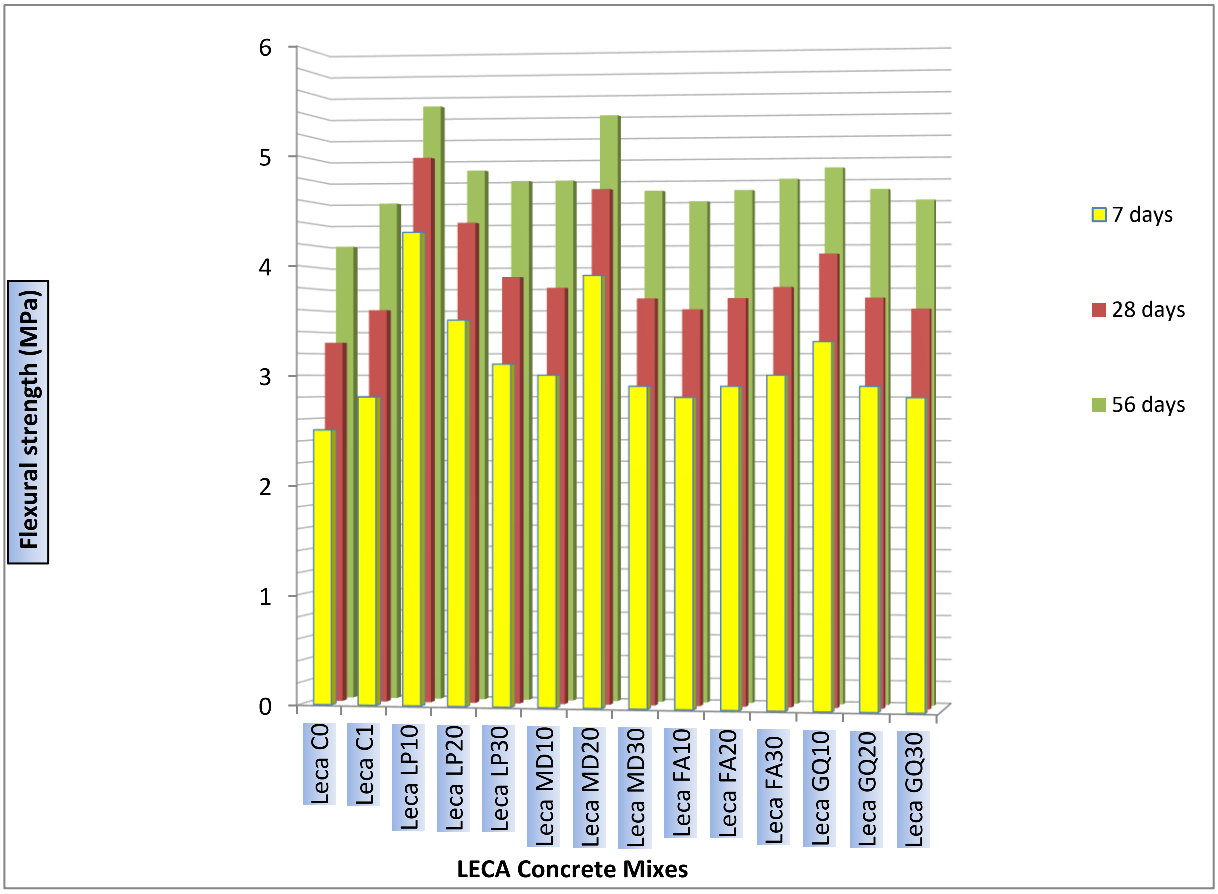

Figure 3:The flexural strength of LECA concrete mixtures.

The flexural strength results followed patterns similar to those observed for compressive and splitting tensile strengths, with some variations in the magnitude of improvement. The control mixtures (LECA C0 and LECA C1) exhibited flexural strengths of 3.3 MPa and 3.6 MPa at 28 days, respectively. The incorporation of silica fumes in LECA C1 resulted in a 9.1% increase in flexural strength compared to LECA C0.

The lime powder-containing mixtures showed flexural strengths of 5.0 MPa, 4.4 MPa, and 3.9 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% lime powder mixture exhibited a remarkable 38.9% improvement in flexural strength compared to LECA C1. This significant improvement can be attributed to several mechanisms:

- Enhanced Interfacial Transition Zone (ITZ): The fine lime particles improve the quality of the interfacial transition zone between the aggregate and paste, which is particularly beneficial for flexural strength.
- Reduced Microcracking: The improved particle packing and reduced water content result in lower drying shrinkage and consequently reduced microcracking.
- Formation of Additional Binding Phases: The reaction between calcium carbonate in lime powder and aluminate phases in cement forms carboaluminate hydrates, which contribute to strength development and crack resistance.

The marble dust-containing mixtures demonstrated flexural strengths of 3.8 MPa, 4.7 MPa, and 3.7 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 20% marble dust mixture exhibited a 30.6% increase in flexural strength compared to LECA C1. This significant improvement can be attributed to similar mechanisms as those for lime powder, including enhanced interfacial transition zone, reduced microcracking, and the formation of additional binding phases.

The fly ash-containing mixtures showed flexural strengths of 3.6 MPa, 3.7 MPa, and 3.8 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. Unlike the other mineral additives, fly ash exhibited progressive improvement in flexural strength with increasing content, with the 30% fly ash mixture showing a 5.6% increase compared to LECA C1. This modest improvement can be attributed to the pozzolanic reaction of fly ash, which contributes to long-term strength development through the formation of additional calcium silicate hydrate (C-S-H).

The granulated quartz-containing mixtures exhibited flexural strengths of 4.1 MPa, 3.7 MPa, and 3.6 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% granulated quartz mixture showed a 13.9% increase in flexural strength compared to LECA C1. This improvement can be attributed to the filler effect and enhanced nucleation provided by the fine-granulated quartz particles.

The flexural-to-compressive strength ratio ranged from 0.13 to 0.17 for all mixtures, which is typical for lightweight concrete and slightly higher than the 0.10 to 0.15 typically observed for normal-weight concrete. This relatively higher ratio can be attributed to the improved quality of the interfacial transition zone resulting from the incorporation of mineral additives and the lower modulus of elasticity of lightweight concrete, which allows greater deflection before failure.

e) Bond Strength

The bond strength results for all LECA concrete mixtures at 7, 28, and 56 days are presented in Figure 4.

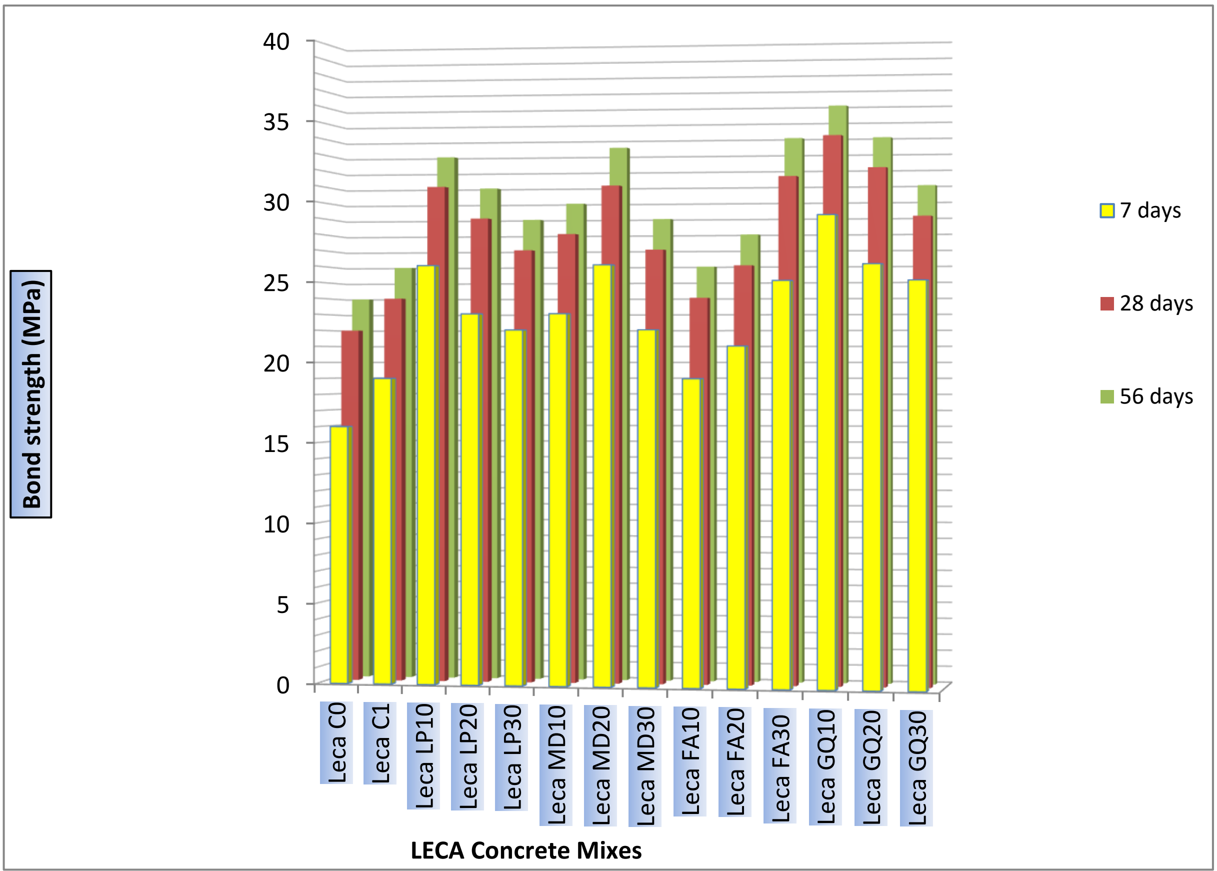

Figure 4: Bond strength of LECA concrete mixtures

The bond strength results demonstrated significant improvement with the incorporation of mineral additives, with variations in the magnitude of enhancement depending on the type and percentage of the additive. The control mixtures (LECA C0 and LECA C1) exhibited bond strengths of 22 MPa and 24 MPa at 28 days, respectively. The incorporation of silica fume in LECA C1 resulted in a 9.1% increase in bond strength compared to LECA C0, which can be attributed to the improved microstructure and enhanced interfacial transition zone.

The lime powder-containing mixtures showed bond strengths of 31 MPa, 29 MPa, and 27 MPa in 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% lime powder mixture exhibited a 29.2% improvement in bond strength compared to LECA C1. This significant improvement can be attributed to several mechanisms:

- Improved Interfacial Transition Zone: The fine lime particles refine the pore structure at the interface between concrete and reinforcement, enhancing the bond characteristics.
- Increased Cohesiveness: The presence of lime powder improves the cohesiveness of the fresh concrete, resulting in better contact with the reinforcement.
- Enhanced Hydration Products: The accelerated hydration and formation of additional binding phases contribute to improved bond strength.

The marble dust-containing mixtures demonstrated bond strengths of 28 MPa, 31 MPa, and 27 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 20% marble dust mixture exhibited a 29.2% increase in bond strength compared to LECA C1. This significant improvement can be attributed to similar mechanisms as those for lime powder, including improved interfacial transition zone, increased cohesiveness, and enhanced hydration products.

The fly ash-containing mixtures showed bond strengths of 24 MPa, 26 MPa, and 31.5 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. Unlike the other mineral additives, fly ash exhibited progressive improvement in bond strength with increasing content, with the 30% fly ash mixture showing a 31.3% increase compared to LECA C1. This substantial improvement can be attributed to the pozzolanic reaction of fly ash, which contributes to long-term strength development through the formation of additional calcium silicate hydrate (C-S-H), particularly at the interfacial transition zone.

The granulated quartz-containing mixtures exhibited bond strengths of 34 MPa, 32 MPa, and 29 MPa at 28 days for 10%, 20%, and 30% addition levels, respectively. The 10% granulated quartz mixture showed a remarkable 41.7% increase in bond strength compared to LECA C1. This significant improvement can be attributed to the filler effect and enhanced nucleation provided by the fine-granulated quartz particles, which refine the pore structure and improve the quality of the interfacial transition zone.

The bond-to-compressive strength ratio ranged from 0.9 to 1.2 for all mixtures, which is typical for self-compacting concrete and higher than the 0.7 to 0.9 typically observed for conventional concrete. This higher ratio can be attributed to the improved interfacial transition zone resulting from the self-compacting nature of the concrete and the incorporation of mineral additives.

f) Comparative Analysis of Different Mineral Additives

The performance of different mineral additives in enhancing the mechanical properties of LECA-based self-compacted lightweight concrete varied based on the type and percentage of the additive, as well as the specific mechanical properties considered. A comparative analysis of the percentage improvement in mechanical properties at 28 days for the best results for each mineral additive relative to the LECA C1 control mixture is presented in Figure5.

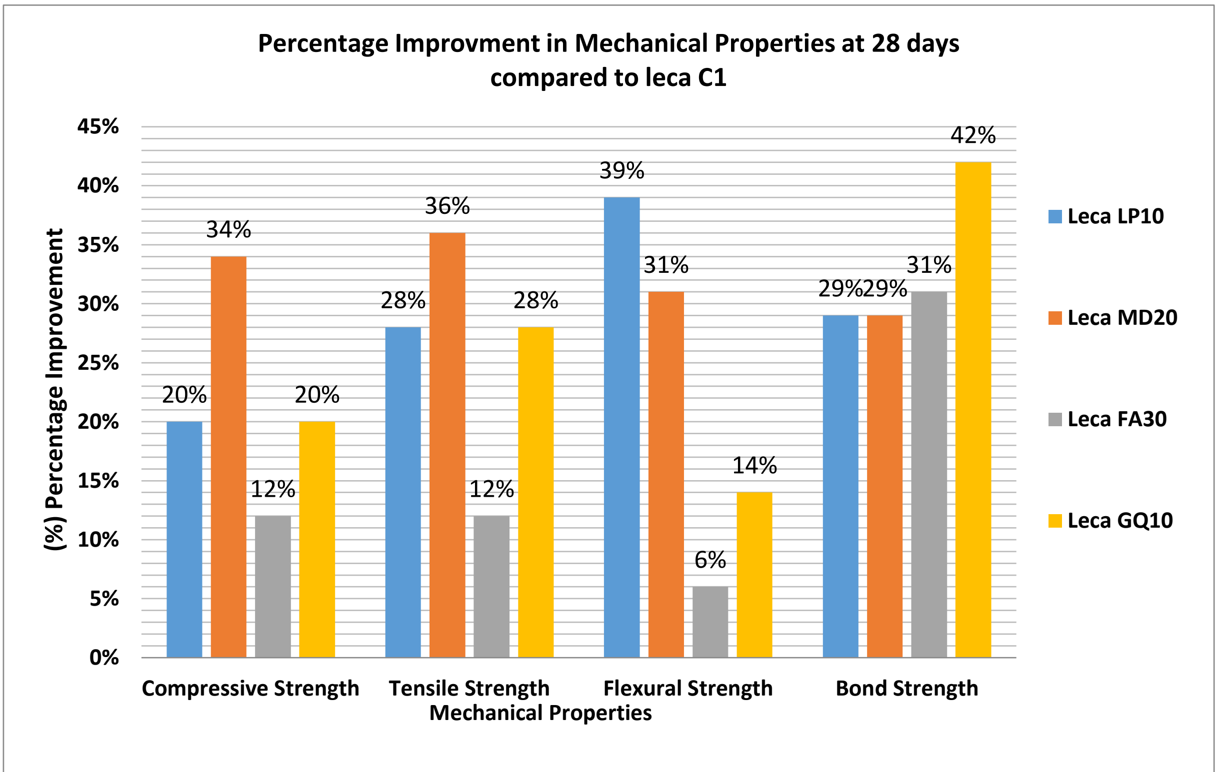

Figure 5: Percentage improvement in mechanical properties at 28 days

The comparative analysis reveals several significant trends in the performance of different mineral additives:

- Compressive Strength: Marble dust at 20% demonstrated the highest improvement in compressive strength (34%), followed by lime powder at 10% and granulated quartz at 10% (both 20%), and fly ash at 30% (12%). The superior performance of marble dust can be attributed to its optimal particle size distribution, which enhances particle packing and reduces porosity.
- Tensile Strength: Marble dust at 20% exhibited the highest improvement in tensile strength (36%), followed by lime powder at 10% and granulated quartz at 10% (both 28%), and fly ash at 30% (12%). The significant enhancement with marble dust can be attributed to the refined microstructure and improved interfacial transition zones, which are particularly important for tensile strength.
- Flexural Strength: Lime powder at 10% demonstrated the highest improvement in flexural strength (39%), followed by marble dust at 20% (31%), granulated quartz at 10% (14%), and fly ash at 30% (6%). The exceptional performance of lime powder in flexural strength improvement can be attributed to its effectiveness in enhancing the quality of the interfacial transition zone and reducing micro-cracking.
- Bond Strength: Granulated quartz at 10% exhibited the highest improvement in bond strength (42%), followed by fly ash at 30% (31%), lime powder at 10%, and marble dust at 20% (both 29%). The remarkable enhancement with granulated quartz can be attributed to its extremely fine particle size, which significantly improves the quality of the interface between concrete and reinforcement.

These results indicate that different mineral additives excel in enhancing specific mechanical properties, with some additives demonstrating more balanced improvement across all properties. Based on the overall performance, the following rankings can be established:

- Marble Dust at 20%: This mixture exhibited the highest average improvement across all mechanical properties (32.5%), with particularly significant enhancement in compressive and tensile strengths. The balanced improvement makes it suitable for a wide range of structural applications.
- Lime Powder at 10%: This mixture demonstrated a high average improvement (29%), with exceptional enhancement in flexural strength. It is particularly suitable for applications where flexural performance is critical, such as beams and slabs.
- Granulated Quartz at 10%: This mixture showed a substantial average improvement (26%), with a remarkable enhancement in bond strength. It is particularly suitable for applications with high reinforcement density or requiring high bond performance.
- Fly Ash at 30%: This mixture exhibited a moderate average improvement (15.25%), with relatively balanced enhancement across all properties. While the improvement is more modest compared to other additives, fly ash offers additional benefits such as reduced environmental impact and improved long-term durability.

The optimal percentage for each mineral additive varies depending on the specific mechanical properties considered. However, as a general observation, moderate replacement levels (10-20%) tend to provide optimal results for lime powder, marble dust, and granulated quartz, while higher replacement levels (30%) seem beneficial for fly ash. This variation can be attributed to the different mechanisms through which these additives influence concrete properties, including filler effects, pozzolanic activity, and nucleation effects.

4. Conclusion

Based on the comprehensive investigation of mechanical properties of self-compacted lightweight concrete manufactured with Light Expanded Clay Aggregate (LECA) and modified with various mineral additives, the following conclusions can be drawn; Lightweight Characteristics: All LECA concrete mixtures achieved densities between 1.70 and 1.75 t/m³, well below the maximum limit of 2.0 t/m³ for lightweight concrete. This confirms the effectiveness of LECA as a lightweight aggregate for structural applications. Self-Compactability: All mixtures demonstrated satisfactory self-compacting characteristics, with flow diameters exceeding 550 mm, J-ring values below 25 mm, and L-box ratios above 0.8. The incorporation of mineral additives generally improved the self-compactability characteristics, with higher mineral additive content resulting in enhanced flowability and passing ability. Compressive Strength: All LECA concrete mixtures achieved the minimum target strength of 25 MPa at 28 days, making them suitable for structural applications. The incorporation of mineral additives significantly enhanced compressive strength, with improvements ranging from 12% to 34% compared to the control mixture with silica fume. Marble dust at 20% demonstrated the highest improvement (34%), followed by lime powder at 10% and granulated quartz at 10% (both 20%), and fly ash at 30% (12%). Tensile Strength: The splitting tensile strength of LECA concrete mixtures was significantly improved through the incorporation of mineral additives, with enhancements ranging from 12% to 36% compared to the control mixture. Marble dust at 20% exhibited the highest improvement (36%), followed by lime powder at 10% and granulated quartz at 10% (both 28%), and fly ash at 30% (12%). Flexural Strength: The incorporation of mineral additives resulted in substantial improvements in flexural strength, with enhancements ranging from 6% to 39% compared to the control mixture. Lime powder at 10% demonstrated the highest improvement (39%), followed by marble dust at 20% (31%), granulated quartz at 10% (14%), and fly ash at 30% (6%). Bond Strength: The bond strength between concrete and reinforcement was significantly enhanced through the incorporation of mineral additives, with improvements ranging from 29% to 42% compared to the control mixture. Granulated quartz at 10% exhibited the highest improvement (42%), followed by fly ash at 30% (31%), lime powder at 10% and marble dust at 20% (both 29%). Optimal Mineral Additive Types and Percentages: Based on the overall performance across all mechanical properties, marble dust at 20% emerged as the most effective mineral additive, with an average improvement of 32.5%. Lime powder at 10% and granulated quartz at 10% also demonstrated substantial enhancements, with average improvements of 29% and 26%, respectively. Fly ash at 30% exhibited more modest but balanced improvements (15.25%) while offering additional environmental benefits. Enhancement Mechanisms: The improvement in mechanical properties can be attributed to several mechanisms depending on the specific mineral additive; Lime powder enhances properties primarily through improved particle packing, accelerated hydration, and the formation of carboaluminate hydrates. Marble dust contributes through optimized particle size distribution, enhanced nucleation effects, and potential chemical interactions with cement components. Fly ash improves properties through pozzolanic reactions, which form additional calcium silicate hydrate and refine the pore structure over time. Granulated quartz enhances performance through its filler effect, providing numerous nucleation sites for cement hydration products and significantly improving the quality of the interfacial transition zone. Property-Specific Optimization: Different mineral additives excel in enhancing specific mechanical properties, providing flexibility in optimization for particular applications. For applications prioritizing compressive and tensile strengths, marble dust at 20% is most effective. For applications emphasizing flexural performance, lime powder at 10% is optimal. For applications requiring high bond strength, granulated quartz at 10% is most suitable. Practical Implications: The findings demonstrate that LECA-based self-compacted lightweight concrete with enhanced mechanical properties can be produced through the strategic incorporation of mineral additives. This opens up possibilities for expanding the application range of lightweight concrete to more demanding structural applications, with potential benefits including reduced structural weight, improved thermal insulation, and enhanced constructability through self-compactability. These conclusions provide valuable insights for engineers and researchers seeking to develop optimized LECA-based self-compacted lightweight concrete formulations with enhanced mechanical properties for specific applications. The ability to tailor the mixture composition based on the desired performance characteristics offers flexibility in addressing diverse construction requirements while maintaining the sustainability benefits of lightweight concrete.

5. Conflicts of Interest

There are no conflicts to declare.

6. Information onFunding Sources

This work is self-funded.

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