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Synergistic effects of vermiculite, pumice stone, and micro-silica on the mechanical and microstructural performance of lightweight concrete

Ananthakumar Ayyadurai[1]*, Saravanan M M[1] and Dineshkumar G[2]
Associate Professor, Department of Civil Engineering, Vivekanandha College of Engineering for Women, Tiruchengode - 637 205, Tamilnadu, India[1]
Associate Professor, Department of Civil Engineering, Vaagdevi College of Engineering, Warangal - 506005, Telengana, India[2]

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Abstract
Lightweight concrete (LWC) is widely used in construction due to its lower density, improved thermal insulation, and enhanced fire resistance. This study investigates the utilization of vermiculite and pumice stone as fine and coarse aggregate replacements, respectively, in LWC, together with micro-silica incorporated at 5%, 10%, 15%, and 20% by weight of cement and a superplasticizer dosage of 0.3%. A comprehensive experimental program comprising 32 mix proportions, each tested in triplicate, was conducted to evaluate the influence of these materials on the microstructural and mechanical performance of LWC. The novelty of this study lies in its detailed investigation of the synergistic effects of vermiculite, pumice stone, and micro-silica on key performance parameters, including density, void ratio, water absorption, and mechanical strength. Among all mixtures, mix number 31 (MN31), containing micro-silica, exhibited the best overall performance, achieving the highest compressive strength (CS) of 17.65 N/mm², satisfying the requirements of ASTM C330 for LWC. The MN31 mix also attained a density of 1438.48 kg/m³, a flexural strength (FS) of 2.84 N/mm², and a split tensile strength (STS) of 1.63 N/mm². Furthermore, microstructural characterization using field-emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDS) revealed improved matrix integrity and refined pore structure, which contributed to the enhanced mechanical performance of the developed LWC.

Keywords
Lightweight concrete, Vermiculite, Pumice stone, Micro-silica; Mechanical properties, Microstructural characterization.

1.Introduction
Lightweight concrete (LWC) is favoured as a modern, environmentally friendly building material is due to its reduced density, improved thermal insulation, and resistance to fire [1]. Natural volcanic aggregates have been used in ancient constructions in the past and are now used in hydroponics, water treatment, and marine structures [2–4]. In countries such as the United States, the United Kingdom, and Sweden, LWC is very popular [5–8]. LWC of structural grade with densities as low as 1980 kg/m3 and adequate strength has been developed [9]. Such qualities are usually achieved through lightweight aggregates (LWA) such as pumice, perlite, polystyrene, and aerogels [10].

It is not easy to achieve high mechanical strength in LWC while retaining low density and durability, though its benefits are overwhelming [11]. The texture and type of the aggregate greatly affect the performance of concrete, bad mix design causes high levels of porosity and reduced strength [12,13]. Workability and ensuring uniform aggregate distribution in the mix are also difficult to maintain when using lightweight elements like vermiculite and pumice [14,15].

To address these issues, the approach employed in this study is optimum aggregate blending, evaluation of performance and modification of microstructures with micro-silica. This study aims at maximizing the LWC mix design through the use of pumice stone and vermiculite as the coarse and fine aggregates respectively. To satisfy the requirements of the American Society for Testing and Materials (ASTM)

*Author for correspondence

C 330, micro-silica and a superplasticizer were used to enhance mechanical strength and durability.

This work presents a comprehensive experimental investigation ion of 32 LWC mixes in a series of three experiments. It evaluates the effect of pumice stone, vermiculite, and various micro-silica contents (5-20 %) in combination with a 0.3% superplasticizer on such key attributes as density, void ratio, water absorption, compressive strength (CS), split tensile strength (STS), and flexural strength (FS). The CS of the mix number 31 (MN31) was best when the CS was 17.65 N/mm^2. Microstructural analysis through field emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDS) confirmed better matrix integrity and reduced porosity. The study promotes the use of LWC in lightweight building by providing a viable and eco-friendly mix design of structural grade.

This study consists of six sections. Section 1 describes the significance of LWC and the background of the research. Section 2 reviews the literature on LWC materials and performance attributes. Section 3 contains the description of the materials, mix design, and experimental procedure. Section 4 presents the results of the durability and mechanical testing. Section 5 discusses the results of the study, including the limitations of the study. Important conclusions are outlined in Section 6 and suggestions on the direction of future research. The references supporting the study are listed at the end.

2.Literature review

The structure of vermiculite is almost identical to that of mica and is highly sheet-like and layered, which enhances bonding capability, insulation, and lightweight properties [16]. Lightweight pumice aggregates together with hybrid fibres of steel and polypropylene have a synergistic impact on increasing the tensile strength, ductility, and impact resistance of concrete [17,18]. The employment of natural pumice helped achieve lower density and higher thermal resistance, whereas the hybrid fibres were effective in inhibiting crack propagation and post-crack behaviour [19, 20]. Fine aggregates were replaced or can be replaced by the Municipal Solid Waste (MSW) inert materials without significantly affecting the mechanical strength of the mortar.

Moreover, the addition of MSW inert generated some change in the sustainability of the mortar in terms of environmental performance, eliminating dependency on natural resources and stimulating the valorization of waste [21, 22]. Bacterial additions improved the mechanical properties of concrete, e.g., its CS and resistance to exogenous factors e.g. moisture, chemicals and temperature variations, etc. [23]. Concrete transparency was achieved through the use of optical fibres by ensuring that the concrete retained some of its mechanical properties including compressive and FS [24].

The incorporation of silica fume and nano-fly ash in the concrete enhanced the mechanical properties of the concrete and also increased the environmental friendliness thereby making it a better plant substrate [25]. Although the admixtures enhanced the workability of the concrete, the hydration process, and the long-term durability of the concrete, fibre addition significantly improved the toughness, impact resistance, and crack control of the concrete [26]. PEG400 enhanced plasticity and durability of the concrete and zeolite increased the strength and long-term stability of the concrete by its pozzolanic effect [27]. Expanded polystyrene (EPS) concrete is one of the widely used materials in energy-efficient structures due to its reduced density that enhances thermal insulation and energy efficiency [28]. LWC has numerous benefits, including higher constructability, reduced dead weight, and high energy efficiency [29]. Basalt stone powder was found to provide good results when incorporated into structural LWC to enhance the mechanical properties of concrete [30]. The physical properties of the non-structural aggregate blocks were good, including thermal conductivity, water uptake, and CS because of their lightweight nature [31]. The cellular foam concrete is suitable in lightweight construction related to favourable mechanical and material properties [32]. The use of waste textile sludge reinforced using Al2O3 nanoparticles has demonstrated the possibility of developing sustainable composite materials [33]. Latent addition of Polyethylene Terephthalate granules to carbon fiber reinforced polymer (CFRP)-laminated concrete beams improved FS and crack resistance, which is likely to be an eco-friendly building material in structural use [34]. The concrete filled steel tubes with normal-weight and LWC were shown to exhibit effective compressive properties when subjected to load and this highlighted their structural efficiency [35]. Also, the utilization of sintered fly ash and electric arc furnace slag in cement was found to enhance the mechanical properties and fracture behavior with further encouraging sustainable construction practices [36]. The ACI 318-08 code is a set of common guidelines to assess the strength and

structural behavior of concrete materials. The provisions are being used in a wide variety of ways to determine the mechanical properties and suitability of LWC for use in structure [37]. The potential of incorporating mineral additives and innovative material combinations in enhancing mechanical properties and durability of concrete systems and provision in the IS codes for the safety and performance requirements has been demonstrated [38–41]. Moreover, sustainable concrete technologies and hybrid material systems have been investigated to promote the use of energy-efficient and efficient concrete in contemporary construction methods [42]. The strength and sustainability of concrete materials can be improved by mineral admixtures like metakaolin and fly ash, which can be used to develop LWC systems with the use of alternative aggregates [43]. Predictive modeling techniques have proven to be useful in assessing the mechanical properties of the concrete mixture and can be used to analyze LWC containing vermiculite and pumice stone. The application of LWA in high-strength, self-compacting, and self-curing concrete is very beneficial in enhancing flow, strength, and durability. Vermiculite swells at 650-1000 ^{0}C. Vermiculite has a bulk density of 130 kg/m^3 [44]. The exfoliated vermiculite of higher quality was used to make LWC with Portland cement among others. Pumice stone is commonly used as an aggregate and mineral admixture in concrete production. It is a naturally formed LWA formed when lava cools and hardens rapidly. This study focuses on pumice and vermiculite stones used in LWC.

Additionally, the impact of microsilica on the formation of an impermeable matrix is also investigated. The mechanical, microstructural, and physical characteristics of LWC that contains pumice and vermiculite stone have been investigated extensively. EDS and FESEM were used to analyze the microstructural characteristics of LWC. The LWA (pumice and expanded vermiculite) was used in dry form without being pre-saturated. To achieve homogeneity in the mixture, the mixing process was carried out in three phases; first, all the dry materials were mixed for 2 minutes followed by the addition of about 70% of the total mixing water, after which the mixture was mixed for 3 minutes; and finally the remaining water was added gradually. Water was added in small increments to ensure consistent workability among the mixes. The reported water-cement ratio was calculated based on the total amount of water added to the mix.

3.Methods

3.1Characteristics of materials

In this study, ordinary Portland cement (OPC-53 grade), having a specific gravity of 3.09 and fineness of 9%, was used in this study. The cement was in accordance with the specification of IS 12269:2013 which specifies the Indian Standards for 53-grade OPC. This standard makes sure that the cement used meets the physical and chemical characteristics within the high-strength concrete application. The cement used in the experimental investigation was tested on several properties before utilization, as required by Indian and ASTM standards in the Indian and ASTM standards. During heating, Vermiculite exfoliates to produce long, concertina-like particles that are lightweight, incombustible, compressible, highly absorbent and non-reactive. The exfoliated vermiculite particles possess a high cation-exchange capacity, and their surface chemistry can be modified to enhance their interaction with cementitious materials. It has various applications such as construction, industries, horticulture and farming. Expanded vermiculite has a specific gravity of 0.11 and a bulk density of 60–130 kg/m^3, an observed expansion temperature of 650 -1100 ^{0}C and a range of particle sizes of 50 microns to 30 mm. The material is heated to such temperatures at a high rate and the exfoliation process occurs in seconds to several minutes. This rapid expansion occurs due to quick heating, which causes rapid steam formation from the interlayer water. Its hardness ranges between 1.5 and 2 on the Mohs scale, and its color varies from brown to bronze-yellow. Vermiculite is a naturally occurring hydrated laminar mineral belonging to the phyllosilicate group. It is commonly used in LWC applications in lightweight applications due to its low density, high porosity, and low thermal conductivity. Expanded vermiculite was used in this paper as a partial replacement in the concrete mix. Its physical properties, including its porous structure and the ability to absorb water were considered during the mix design process. Its effect on the fresh and hardened properties of LWC was evaluated using this material. Pumice stone is a LWA which is formed from hydrated basaltic minerals. It is partially expandable and medium shrink–swell capacity. Pumice is normally pale in colour. Amorphous silica is a fine pozzolanic material obtained as a by-product of the production of elemental silicon or ferrosilicon alloys. The natural pumice aggregates come in three fractions, namely, sand (0-4 mm), fine (4-8 mm), and coarse (8-16 mm). The pumice used in this experiment is fine grade between 4-8 mm. Pumice stone has a specific gravity of 0.92, water absorption

of 2.3%, and a crushing strength of 3.4 MPa. XRD analysis was performed under Cu Kα radiation (λ=1.5406 A) at 40 kV and 30 mA. The scans were conducted at a 2θ range of 5^0 to 80^0 with a step size of 0.02^0 and a scanning rate of 2^0/min. The existence of an amorphous phase was qualitatively measured by the broad hump in the range of 20^0C-35^0C 2θ. The XRD analysis shows that the pumice is mainly comprised of small crystalline phases, which include quartz and low cristobalite (S_iO_2) minerals. Though these crystalline components are in smaller amounts, they indicate a high silica content in the pumice since the data on the chemical composition in *Table 1* supported these findings. The analysis also indicates that the remaining oxides found in the pumice sample is mostly in its amorphous glassy form, mixed with the silica skeleton. Such a high silica content together with an amorphous glassy phase indicates that the pumice is pozzolanic, which may play a role in the hydration process in cement-based systems. Pumice is a naturally occurring volcanic rock with high porosity and low weight. It is mainly composed of amorphous aluminosilicate compositions with high silica content. Pumice is usually a low-specific gravity material that has high porosity thus making it suitable for LWC applications. The importance of pumice in the concrete mix as a partial replacement material was tested in this study to determine its effect on the properties of LWC. *Figure 1* illustrates the block diagram of this research.

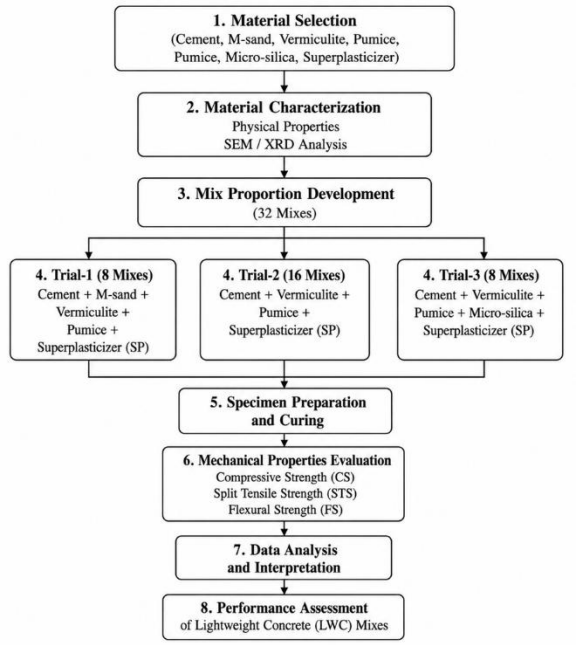


Figure 1 Schematic representation of the experimental methodology

3.2Admixtures

For the present investigation, micro silica was used at the dosage of 5%, 10%, 15% and 20% by weight of cement. The microsilica used in this experiment had a mean particle size of about 150 nm, as reported in the manufacturer's technical datasheet. The surface area was about $20m^2/g$ and the loss on ignition (LOI) was less than 6%. The particles observed by scanning electron microscope (SEM) were found to exist in agglomerated clusters, as is characteristic of silica-based fine materials. The material properties meet the ASTM C1240 requirements for silica fume used in cementitious systems. Adding 0.3% superplasticizer (Ceroplast-300) contributes to a higher level of water reduction and improved workability without variance in the setting time [7]. Micro-silica, also known as silica fume, is a fine by-product of silicon and ferrosilicon alloy production, consisting primarily of silica (SiO_2). It is usually employed in LWC to develop numerous properties as a result of being highly reactive and having a small particle size. Micro-silica is used as an admixture in several ways: it occupies the space between larger particles, thereby increasing workability; it has a pozzolanic property and, therefore, increases strength and durability; and also it decreases the amount of water used whilst maintaining workability. Micro-silica in combination with LWC contributes significantly to CS, STS, and FSs and enables thinner structural elements to be made without compromising the load-bearing capacity. It also lowers the void ratio, creating a denser matrix that mitigates porosity and shrinkage issues.

Additionally, it improves durability by reducing permeability and enhances microstructural properties. This aids in achieving higher early-age strength in LWC. The chemical composition and physical properties of the materials used in this investigation are shown in *Tables 1* and *2*, respectively.

3.3Mix proportions

In this research, the mix proportions are derived based on the volume batching method. A total number of thirty-two mix proportions corresponding to three test series are considered for studying the mechanical and microstructural properties of LWC. In Trial-1, eight mix proportions are investigated using cement, M-sand and Vermiculite. Superplasticizer is added at a dosage of 0.3 % based on the weight of cement. In total, sixteen mix proportions are investigated in Trial-2, and the materials used are cement, vermiculite, pumice stone, and admixture (coroplast-300). Pumice stone is used

instead of M-sand. Based on the test results, trial-3 proposes incorporating micro-silica with LWC, vermiculite, and pumice stone. Micro-silica is added at 5%, 10%, 15% and 20% by weight of cement and eight mix proportions are investigated in Trial-3. The mix proportions investigated in all three trials are given in *Table 3*. The percentage ratios were derived through a progressive screening method to measure the trends of performance. The design of the study does not presuppose a formal factorial or response surface optimization design; instead, it is proposed to find a viable and balanced combination of LWC referring to experimental performance measurement criteria.

Table 1 Chemical composition of materials (Wt.%)

	Cement	**Vermiculite**	**Pumice stone**	**Micro-silica**
SiO_2	21.04	11.92	63.50	97
Al_2O_3	6.02	43.48	14.56	0.3
Fe_2O_3	3.77	-	2.12	0.5
CaO	62.93	-	3.16	0.3
MgO	2.59	14.35	3.80	0.5
FeO	-	10.82	-	-
Cl	0.07	-	-	0.01
Na_2O	0.19	-	4.66	0.24
K_2O	-	-	4.50	0.5
TiO_2	-	-	0.30	-
SO_3	1.72	-	0.60	0.15
LoI	1.76	-	2.80	-

Table 2 Physical properties of materials

Materials	**Specific gravity**	**Density (kg/dm^3)**
Cement	3.09	3.09
M-sand	1.602	1.602
Expanded Vermiculite	0.11	0.11
Pumice stone	0.92	0.92
Micro-silica	2.26	2.26
Water	1	1

Table 3 Mix the proportion of prepared LWC (quantity of single volume)

Mix ID	**Materials**	**Ratio**	**Cement**	**M-Sand**	**Vermiculite**	**Pumice stone**	**Micro-silica (g)**
MN1	Trial-1 -Cement: M-Sand: Vermiculite: Superplasticizer	1:0.5:2	0.90	1.15	0.35	-	-
MN2		1:0.5:4	0.90	1.15	0.70	-	-
MN3		1:0.5:6	0.90	1.15	1.05	-	-
MN4		1:0.5:8	0.90	1.15	1.40	-	-
MN5		1:1:2	0.90	2.30	0.70	-	-
MN6		1:1:4	0.90	2.30	1.40	-	-
MN7		1:1:6	0.90	2.30	2.10	-	-
MN8		1:1:8	0.90	2.30	2.80	-	-
MN9	Trial-2 -Cement: Vermiculite: Pumice Stone: Super plasticizer	1:0.5:0.5	0.90	-	0.35	0.20	-
MN10		1:0.5:1	0.90	-	0.35	0.40	-
MN11		1:0.5:1.5	0.90	-	0.35	0.60	-
MN12		1:0.5:2	0.90	-	0.35	0.80	-
MN13		1:1:0.5	0.90	-	0.70	0.20	-
MN14		1:1:1	0.90	-	0.70	0.40	-
MN15		1:1:1.5	0.90	-	0.70	0.60	-
MN16		1:1:2	0.90	-	0.70	0.80	-
MN17		1:1.5:0.5	0.90	-	1.05	0.20	-
MN18		1:1.5:1	0.90	-	1.05	0.40	-
MN19		1:1.5:1.5	0.90	-	1.05	0.60	-
MN20		1:1.5:2	0.90	-	1.05	0.80	-

Mix ID	Materials	Ratio	Cement	M-Sand	Vermiculite	Pumice stone	Micro-silica (g)
MN21		1:2:0.5	0.90	-	1.40	0.20	-
MN22		1:2:1	0.90	-	1.40	0.40	-
MN23		1:2:1.5	0.90	-	1.40	0.60	-
MN24		1:2:2	0.90	-	1.40	0.80	-
MN25		1:0.5:2:5	0.90	-	0.35	0.80	45
MN26		1:0.5:2:10	0.90	-	0.35	0.80	90
MN27	Trial-3 -Cement:	1:0.5:2:15	0.90	-	0.35	0.80	135
MN28	Vermiculite: Pumice	1:0.5:2:20	0.90	-	0.35	0.80	180
MN29	Stone: Micro-silica:	1:0.5:2.5:5	0.90	-	0.35	1	45
MN30	Super plasticizer	1:0.5:2.5:10	0.90	-	0.35	1	90
MN31		1:0.5:2.5:15	0.90	-	0.35	1	135
MN32		1:0.5:2.5:20	0.90	-	0.35	1	180

3.4Manufacturing of test specimens

Thirty-two mix proportions were developed to assess the performance of LWC incorporating vermiculite, pumice stone, micro-silica, and a superplasticizer. The preparation involved a systematic approach, beginning with careful selection and weighing of materials, including OPC, vermiculite as fine aggregate, pumice stone as coarse aggregate, and varying percentages of micro-silica (5%, 10%, 15%, and 20%) with a constant superplasticizer dosage of 0.3%. Dry ingredients were blended to achieve homogeneity using a mechanical mixer and water and superplasticizer were added gradually in order to increase workability. The prepared concrete was then poured into standardized cube (150 mm × 150 mm), cylinder (150 mm × 300 mm), and prism (100 mm × 100 mm × 500 mm) moulds and compacted using a vibrating table to remove air bubbles. The specimens were then cast and covered to avoid loss of moisture and allowed to cure for 24 hours and then they were demoulded and immersed in a curing tank of 7 to 28 days to achieve maximum hydration. Once the curing period was complete, the specimens underwent various tests, including CS tests for cubes, STS tests for cylinders, and FS tests for prisms. *Figure 2* shows the curing of cast specimens. The fresh concrete was then transferred to steel moulds and compacted using a vibrating table.



Figure 2 Curing of cast concrete cubes in a water tank to maintain hydration

4.Results

4.1Void ratio

The volume of the voids in the LWC was determined based on the standard formula of the volume of the voids to the volume of solids, and the data is shown in *Figure 3.* The graphical analysis shows that the percentage of void ratio increases gradually up to the MN4 mix (Trial-1), and beyond that, a decreasing pattern is observed. Thus, mix MN4 (Trial-1) exhibited the maximum void ratio of 72.55% among all other mix proportions, and the lowest value has been recorded as 37.97% for the MN5 mix. Similarly, 36.91% (MN16) and 13.98% (MN10) are the maximum and minimum void ratio of Trial 2 respectively. Though the mixes of MN5 and MN10 (Trial-1 and Trial-2) revealed the lowest void ratios, the strength values are comparatively low. Similarly, MN27of Trial-3 has a record of 13.89% (lowest void ratio), but the CS value is noted as 9.3 N/mm^{2,} which is not found to be satisfactory.

The results reveal a complex relationship between void ratio and CS across the different mix proportions of LWC. The mix exhibiting the optimum void ratio, namely, MN4, appears to provide a good trade-off between the air content and the composition of the material, which also contributes to better performance characteristics. This indicates that it is possible to maintain the lightweight characteristics of the material while moderate void ratios may enhance structural integrity and positively influence LWC.

Conversely, mixes such as MN5 and MN10, which exhibited the lowest void ratios, did not achieve satisfactory CS. This suggests that maintaining a moderate void ratio can improve structural integrity while preserving the lightweight characteristics of LWC. On the same note, in Trial 3, the mix of MN27 exhibited a low void ratio but the CS of this mix was

still unsatisfactory, which confirms that void ratio is not the only determinant of the strength of a material. These factors include aggregate distribution, the incorporation of micro-silica, as well as the overall composition of the material and should be well balanced to ensure lightweight properties and structural stability.

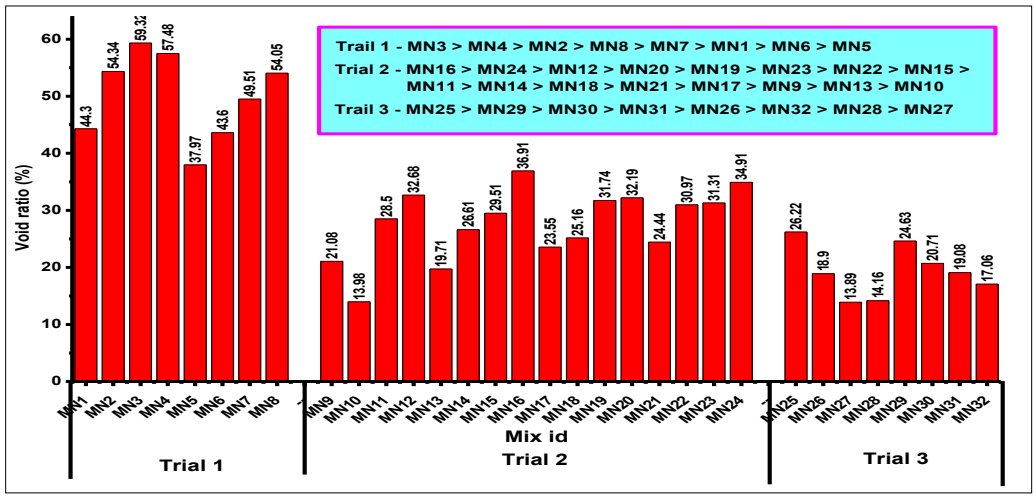


Figure 3 Variation in void ratio across multiple concrete mix trials

4.2 Water absorption

All the mix proportions of Trial-1 have exhibited a higher range of water absorption (as per ASTM C642) than Trial-2. Based on performance observations from Trial-2, Trial-3 was developed. Maximum and minimum water absorption values that are observed in Trial-2 are 12% (MN24) and 2% (MN9) respectively. Trial-3 is considered for further investigation because all the mixed proportions of it have a record of low range of water absorption (*Figure 4*). Even though the minimum value of water absorption in the mix MN25 (Trial-3) is observed to be 2.7%, the CS is not up to the recommended value.

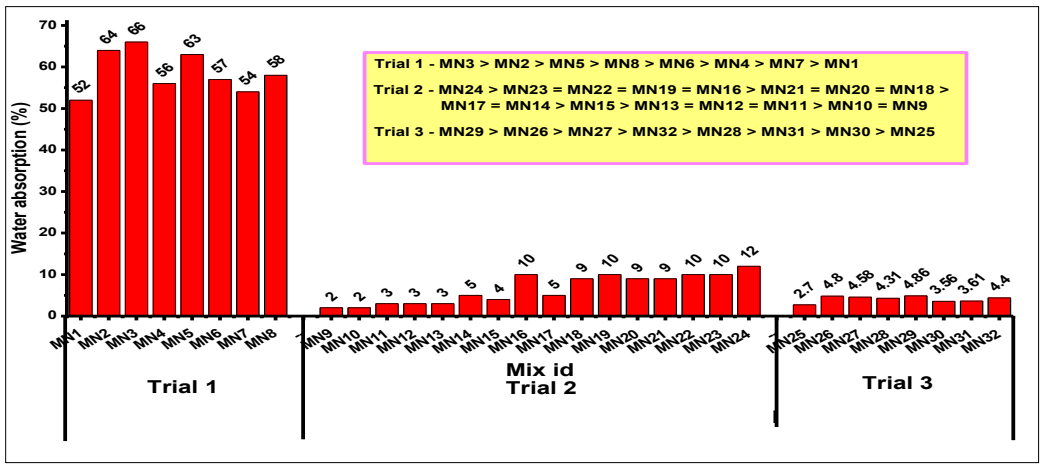


Figure 4 Comparison of water absorption in percentage for various concrete trial mixes

The obtained results of water absorption show significant differences between the mix proportions of Trial-1 and Trial-2. Trial-1 showed slightly large values of water absorption as compared to Trial-2, mainly because it had M-sand and a larger void structure because of the use of LWA combinations at the beginning. Trial-2, on the other hand, employed pumice stone in addition to the vermiculite, which led to a better packing of particles as well as fewer interconnected voids and consequently lower values of water absorption (between 12 and 2 percent in MN24 and MN9 respectively). These results indicate

that the optimized aggregate mixture in Trial-2 helped to achieve better compactness of the matrix and less porosity. Further investigation of Trial-3 revealed that all its mix proportions exhibited a low range of water absorption, making it promising for applications requiring enhanced durability. Nonetheless, the MN25 mixture, as shown by Trial-3, had a low water absorption value, which was 2.7, however, the CS of this mix was below the required standards. This indicates that although minimizing water absorption is desirable for enhancing durability, it is not always directly proportional to increased CS. Hence, when optimizing LWC mixes for structural applications, a balanced approach should be adopted between water absorption and CS.

4.3Density

In the fresh and hardened stages, the density of the concrete was determined (according to ASTM C567). *Figure 5* indicates wet and dry density of 32 mix proportions were investigated (MN1-MN32). In Trial-3, the density of the mix proportions ranged from 1400-1500 Kg/m^3. The lowest wet and dry density value is 1305.13Kg/m^3 & 1407.55Kg/m^3, respectively, in the case of MN29 mix (Trial-3). The density of hardened concrete may vary depending on several factors, but as a rule, it tends to be lower than the fresh density. The main factors contributing to this difference are the loss of water, compaction and shrinkage, aggregate settlement and porosity or microcracks.

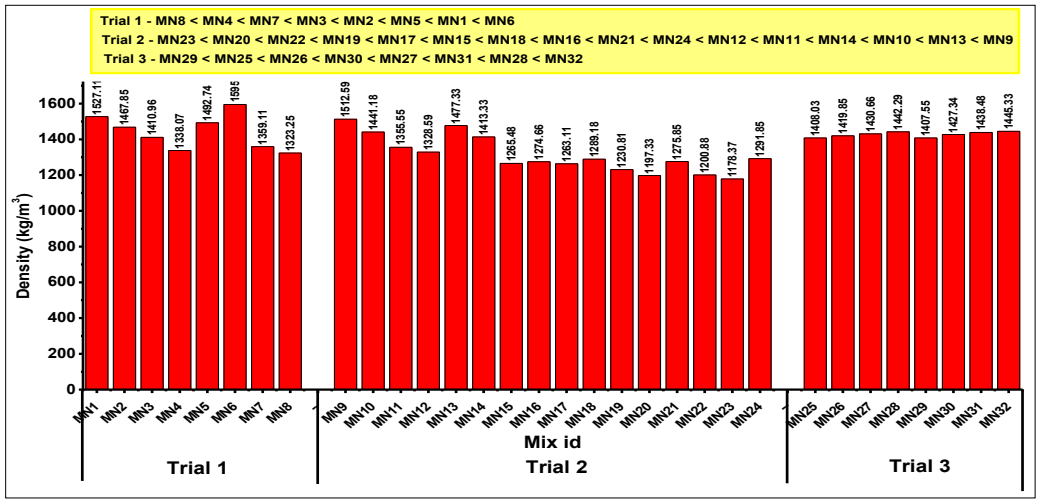


Figure 5 Variation in density factor across the multiple concrete trial mixes

These results indicate the necessity of considering the variation of density between fresh and hardened phases when designing LWC. The decrease in density, as expected, may influence the overall performance of concrete, particularly with regard to structural stability and strength. It therefore becomes important to exercise caution in balancing the need to achieve sufficient strength while maintaining a low density for lightweight properties. The low density observed in Trial-3 implies that it would possibly be applicable in applications that emphasize weight reduction. Nevertheless, the strength implications must also be evaluated further to ensure that the performance standards are satisfied.

4.4Compressive strength

CS was tested at 7, 14, and 28 days of its curing. As a rule, LWC has a lower CS than conventional concrete because of the LWAs which are more porous. ASTM C330 provides a minimum CS of 17MPa at 28 days in structural LWC. Cement MN1-MN8 mixes were trial mixes of cement, M-sand and vermiculite in different ratios. The values of CS were varied slowly with the adjustment of the mix proportions. The CS of MN1 was the lowest and possibly this can be explained by the increased vermiculite content. Vermiculite is a lightweight and porous mineral and thus it increases the internal void ratio and decreases the overall density of the matrix, which decreases the strength. With the increase in the percentage mixing of M-sand like MN5 and MN6, the CS rose as a result of higher particle packing and lesser void spaces. M-sand aided in enhancing the densification of the cementitious structure, and the load transfer. Mixes MN7 and MN8 were found to have relatively high CSs in this trial exercise, which implies that optimum proportions between M-sand and vermiculite are key to attaining enhanced mechanical performance. Nevertheless, when the vermiculite level was too high, it always led to a decreased

strength because the porosity level was high, and the interfacial bonding was weak.

The mixes used in Trial-2 (MN9-MN24) had cement, vermiculite and pumice stone. The presence of pumice stone modified the internal framework of the concrete, with pumice stone being porous and at the same time comparatively stronger than vermiculite. MN9 and MN10 had lower CS values (6.03 MPa and 6.48 MPa, respectively), probably because of increased LWA content, which increased internal voids and reduced structural compactness. With the pumice stone proportion optimized with mixes like MN11 and MN12, CS was enhanced as a result of the increased aggregate interlocking as well as, the increased packing density. The mixes MN13 to MN15 showed medium strength gains, which showed enhanced interaction of cement paste and LWA. However, blends such as MN21 to MN24 had lower strengths, which was mainly due to high proportions of LWA which pushed into porosity and weakened cohesive bonding in the matrix. All the Trial-2 mixes did not reach a minimum CS of 17 Mpa as set forth by ASTM C330 at 28 days meaning that additional matrix densification was needed (*Figure 6*). Trial-3 (MN25-MN32) used micro-silica as an additional cementitious material in place of cement, vermiculite, and pumice stone. Micro-silica addition was found to contribute a lot in CS, its ultrafine particle size and pozzolanic reactivity. Micro-silica aided in the filling of micro-voids in the cement matrix, enhancement of pore structure and enhancement of Interface Transition Zone between aggregates and paste. Interestingly, MN25, and MN26 showed some improvement over the past trials, albeit the strength of the result was still affected by LWA proportions. Mixes MN27 to MN30 exhibited an increase in strength with increase in micro-silica dosage. The CS of MN31 was the highest with 17.65 Mpa at 28 days and this is in compliance with the ASTM C330 structural LWC. The better performance of MN31 can be explained by the fact that the combination of vermiculite, pumice stone and micro-silica was optimized, which led to the enhanced particle packing, lower connectivity between voids, and increase in the cohesion of the matrix. MN32 (16.11 MPa) also was also performing very well, but still slightly lower than ASTM requirement. These findings affirm that the introduction of micro-silica in Trial-3 was a significant factor in the realization of structural-grade lightweight performance of concrete. *Table 4* provides the summary of the results of CS of all mixes on a 28 day basis. Trial-1 had low values of strength than Trial-2 and Trial-3. MN31 (17.65 ± 0.55 Mpa) had the highest CS and this met the ASTM C330 requirement.

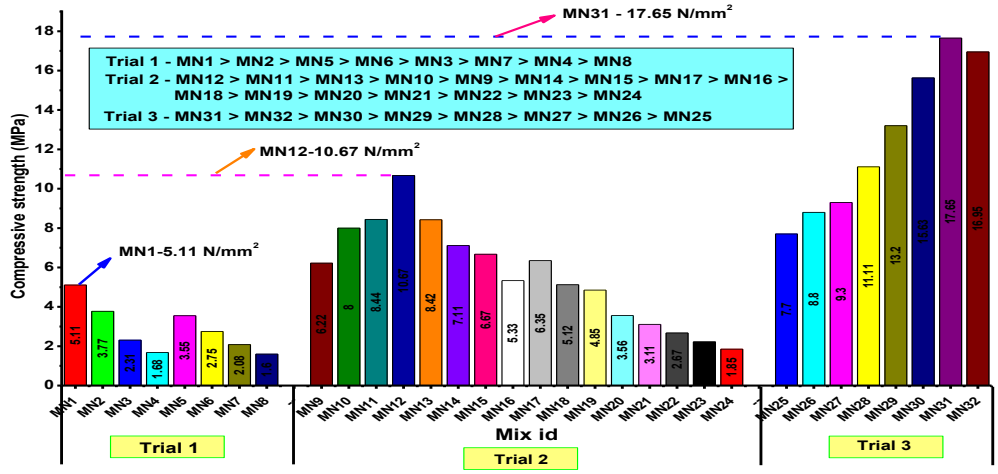


Figure 6 Measured CS values for selected trial mixes used in the study

Table 4 Statistical summary of 28-Day CS for all trial mixes (Mean ± SD, n = 3) and ASTM C330 compliance

Trial	Mix ID	28-Day CS (MPa)	Mean ± SD (MPa)	ASTM C330 Compliance
Trial-1	MN1	5.11	5.11 ± 0.18	Not Satisfied
Trial-1	MN8	1.60	1.60 ± 0.07	Not Satisfied
Trial-2	MN13	10.67	10.67 ± 0.32	Not Satisfied
Trial-2	MN24	1.85	1.85 ± 0.08	Not Satisfied
Trial-3	MN31	17.65	17.65 ± 0.55	Satisfied
Trial-3	MN25	7.77	7.77 ± 0.24	Not Satisfied

4.5Split tensile strength

In Trial-1, eight distinct mix proportions were assessed for STS (*Figure 7*). Among them, MN1 had the greatest STS value, followed by MN5, which was 0.38 N/mm² less than MN1. However, compared to the other mixes in this testing, mixes MN5 and MN4 showed much lower STS levels. The first four mixes' (MN1, MN2, MN3, and MN4) STS values gradually decreased. Following a significant increase in MN5, STS levels steadily decreased from MN6 to MN8. Trial 1's STS values are MN1 > MN5 > MN2 > MN6 > MN7 > MN3 > MN4 > MN8. Trial 1's total STS values were lower than those of previous trials because no solid particles were in the mix proportions. The mixtures, which included cement, Vermiculite, and M-sand, formed a liquid-like consistency. Vermiculite's tremendous propensity to absorb water caused it to operate as a moisture-retaining agent, which decreased its strength. Despite a low void ratio, these mixes' tensile strength was significantly reduced by the absence of solid aggregates because the cohesive force inside the matrix was inadequate to withstand tensile stresses. To overcome the limitations of Trial-1, pumice stone was used as a coarse aggregate in place of M-sand in Trial-2, which included 16 mix proportions (MN9 to MN24). This modification aimed to improve the concrete matrix's structural stability. MN12 had the highest STS value in Trial-2, while MN24 displayed the lowest value (0.22 N/mm^2), even lower than MN8 in Trial 1. In Trial-2, the STS values gradually increased from MN9 to MN12 before declining from MN13 onwards.

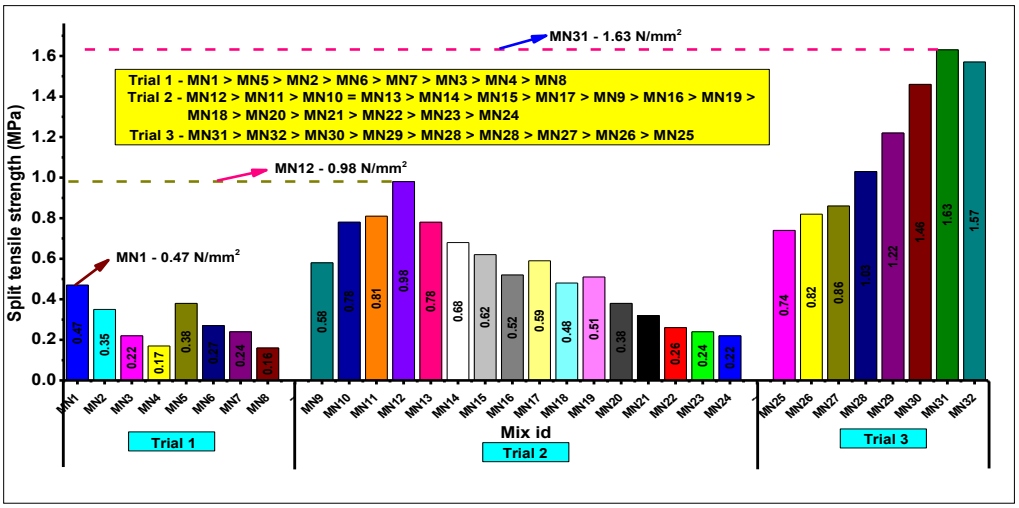


Figure 7 Measured STS values for selected trial mixes used in the study

Remarkably, MN10 and MN13 had identical STS values, suggesting that performance decreased at these particular mix proportions. The average STS value for MN17 and MN10 remained at 0.55 N/mm². MN12 > MN11 > MN10 = MN13 > MN14 > MN15 > MN17 > MN9 > MN16 > MN19 > MN18 > MN20 > MN21 > MN22 > MN23 > MN24 is the order of the STS values in Trial 2. A higher void ratio based on an imbalance in the mix proportions was identified as the reason for the decrease in STS values in mixes like MN24, MN23, and MN22. At first, using pumice stone improved the structural performance; however, when too many lightweight particles were added, the strength decreased. In addition to the pozzolanic action of micro-silica, which enhanced matrix cohesion and decreased porosity, MN12, which obtained the highest STS value, benefited from an ideal ratio of cement, pumice stone, and Vermiculite.

In contrast to Trial-1, Trial-2 and Trial-3, which included mixes of MN25 to MN32, showed a notable improvement in STS values. This experiment used micro-silica as an additional material to enhance the strength properties. The values of STS increased with MN25 to MN31 with MN31 having the highest STS value of all 32 mixes. Meanwhile, MN32 exhibited a sharp loss of STS that was attributed to an unbalance in the concentration of the micro-silica. This might have led to over densification which caused micro-cracking of the under tensile stresses. The order of the STS values in Trial-3 is MN31 > MN32 > MN30 > MN29 > MN28 > MN27 > MN26 > MN25. The Trial-3 mixtures performed better due to the addition of micro-silica, which served as a filler material and enhanced the packing of the particles and reduction

of the number of voids. This was due to the stronger tensile strength caused by better bonding within the matrix through the optimization of mix proportions. The drop in MN32, though, highlights the importance of maintaining a controlled amount of microsilica dosage to avoid excessive compaction and concomitant shortcoming.

4.6Flexural strength

The FS test was performed on each specimen after the CS and STS. Following the test, the MN31 mix achieved the highest FS value compared to the other trials (Trials-1, 2, and 3). In particular, the trial one mix FS findings (*Figure 8*) show a notable increase in the value of FS on MN5 and a progressive reduction from 0.84N/mm^2 (MN1). The FS obtained in MN2 and MN5 is the same. MN1>MN2=MN5>MN6>MN3>MN7>MN4>MN8 is the order of trial-1. Due to the unsatisfactory results, the study was extended to trial 2. Instead of using M-sand in trial 1, the pumice stone was used in trial-2. The workability parameters were satisfactory when the pumice stone was introduced. In trial-2, a total of sixteen mix proportions were investigated. The highest FS value obtained was MN12, and MN13 came in second. The remainder of the mix proportions have been somewhat lowered to 0.63N/mm^2 (MN24). MN23 is the mix with the lowest FS value. The FS value of 1.74N/mm^2 is slightly higher for MN9 to MN12.

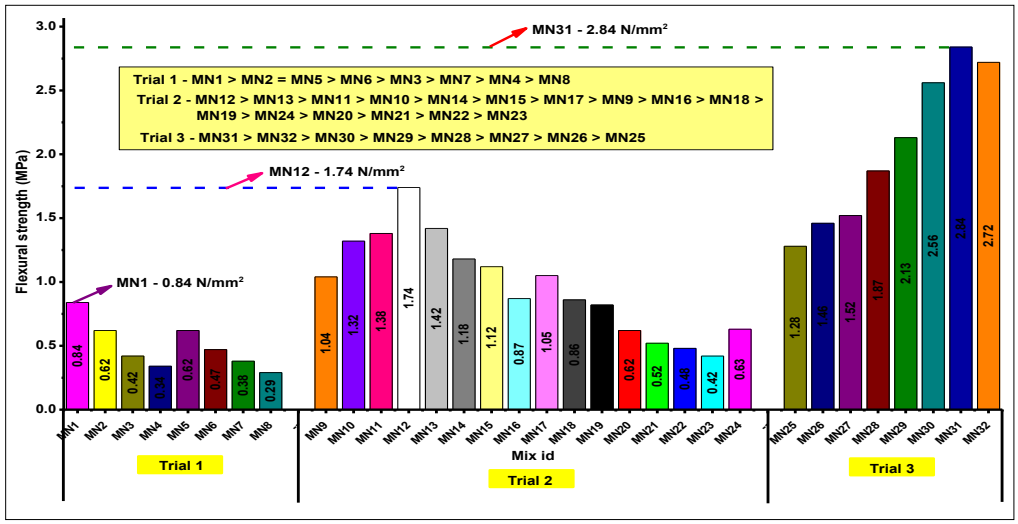


Figure 8 Measured FS values for selected trial mixes used in the study

Following that, the aggregate's crushing strength and voids would cause the FS value to decrease. Pumice stone is a naturally light substance that crushes quickly and absorbs more water. After that, the concrete was subjected to loads that caused it to break readily and reduce its capacity to support loads. Therefore, the incorporation of a more effective admixture in Trial-3 was considered necessary to further enhance the mechanical performance. For this reason, the microsilica additive is added to the LWC mixture in Trial-3.

Eight different mix proportions were investigated in Trial-3. The FS value increased progressively from MN25 to MN31, with MN31 achieving the highest FS value. Although MN32 exhibited a slight decrease in FS compared with MN31, its performance remained comparable. Therefore, MN31 demonstrated the optimum flexural performance among all Trial-3 mixes. MN25 exhibited an FS value of 1.28 N/mm². This value was higher than the maximum FS obtained in Trial 1 and comparable to the lower range of values observed in Trial-2. The FS value further increased to 1.87 N/mm² for MN28, demonstrating a notable improvement compared with the mixes in Trials-1 and 2. The value was further increased to 2.84 N/mm^2 (MN31). MN31>MN32>MN30>MN29>MN28>MN27>MN26>MN25 is the FS range for Trial-3. Compared to all experimental mixes, MN31 achieved the highest and best value of FS.

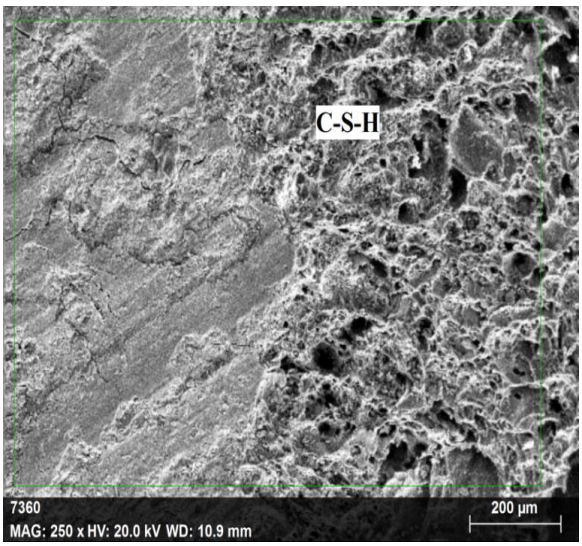
4.7FESEM and EDS analysis

The microstructural characteristics of tested samples are assessed using FESEM analyses. The development of C-S-H in LWC is visible in FESEM pictures. C-S-H gel formation and chemical dispersion in MN31 are depicted in *Figure 9*. The

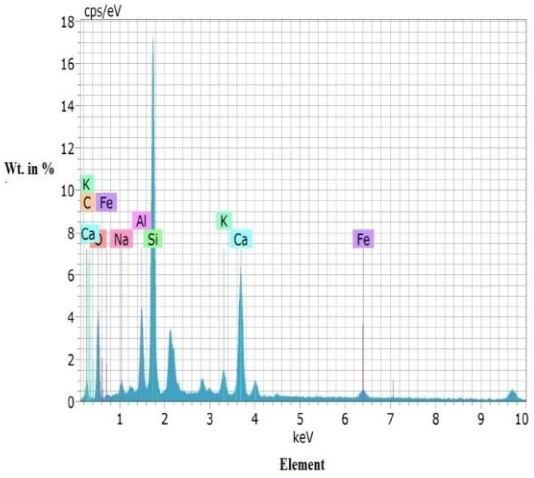
EDS map shows the rise in calcium and silicate content in the LWC. SEM examination demonstrates the beginning and progression of the crack in LWC, which develops around LWA. It is shown that the pores are smaller and have little connection. SEM images demonstrate a higher level of calcium-silicate-hydrate production, which enhances strength characteristics. As a result, this mix exhibited the highest mechanical strength among all the investigated combinations.

SEM analysis clearly illustrates the initiation and propagation of cracks in the LWC, primarily around the LWA, as shown in *Figures 10(c)* and *10(d). Figures 10(e)* and *10(f)* reveal a refined pore structure with smaller and less interconnected pores, contributing to the improved mechanical performance. In contrast, *Figure 11* presents the C-S-H formation and chemical composition of mix MN25, which exhibited weaker bonding characteristics and a less dense microstructure. As a result, the CS is decreased. Cracks can be seen to develop around the matrix's LWA in the photos (*Figure 12*: Morphology View). When the concrete is loaded to its maximum capacity, these fissures appear. The chemical makeup of the mixes (MN25 & MN31) is displayed by EDS mapping, and ultimately, it is noted that the MN31 mix performs better than the MN25 mix.

FESEM was used to conduct the microstructural analysis of LWC which was used to give information of the internal structure of the experimental samples. Formation of C-S-H gel, which increases the strengths characteristics of LWC, was measured based on EDS atomic ratios (Ca/Si), elemental maps were generated at the same magnification and scale bars were provided to compare them accurately. Various bedsides were studied in order to make representative analysis. To reduce artifacts, the preparation of the samples included drying, gold sputtering, and their adequate mounting. Supported by FESEM images, it can be seen that the MN31 mix has a more intense C-S-H form and reduced cracks in contrast to M25, which is attributed to a denser matrix, as a result of enhanced particle packing, and greater bonding. Microsilica also facilitates pozzolanic reactions, which promotes the formation of C-S-H gel, whereas porous pumice facilitates mechanical interlock and vermiculite promotes internal curing. Cracking at and around the LWA is also accentuated in the annotated micrographs, it is indicated that the low pore size and low connectivity are conducive in reducing the crack propagation.



(a)C–S–H gel formation in MN31 mix



(b)EDS elemental analysis

Figure 9 SEM image showing C–S–H gel formation in MN31 mix with corresponding EDS elemental analysis

In contrast, the microstructural analysis of the MN25 mix reveals unsatisfactory binding behaviour, with cracks developing around the LWA under maximum load. This poor binding results in reduced CS compared to the MN31 mix. EDS mapping of both mixes further supports these findings, with MN31 showing a more favourable chemical composition, ultimately leading to improved performance. Overall, the microstructural analysis confirms that the MN31 mix outperforms MN25 in strength and durability, primarily due to the enhanced formation of C-S-H gel and better pore structure.

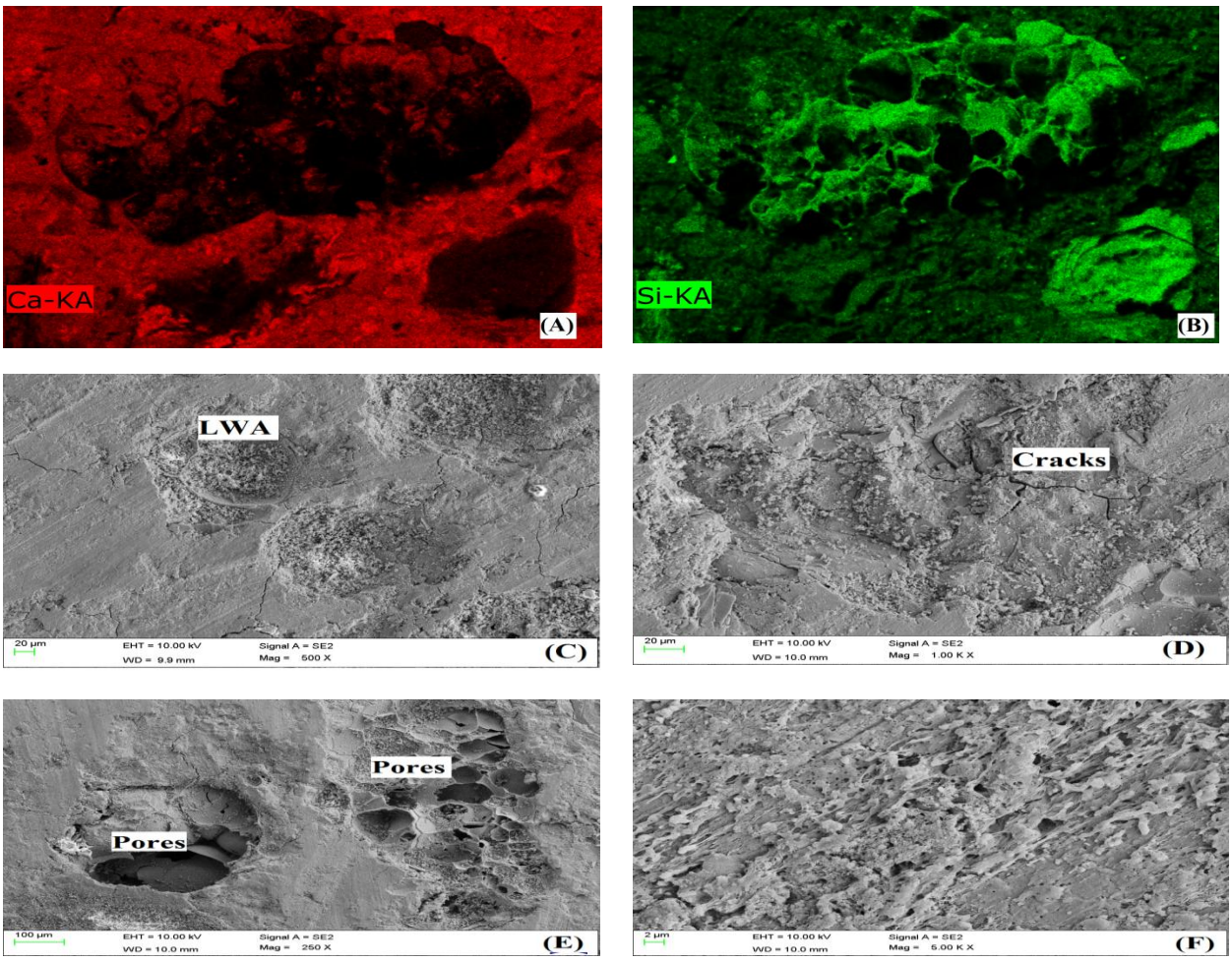


Figure 10 After-test SEM morphology of MN31 LWC showing surface texture and microstructural changes

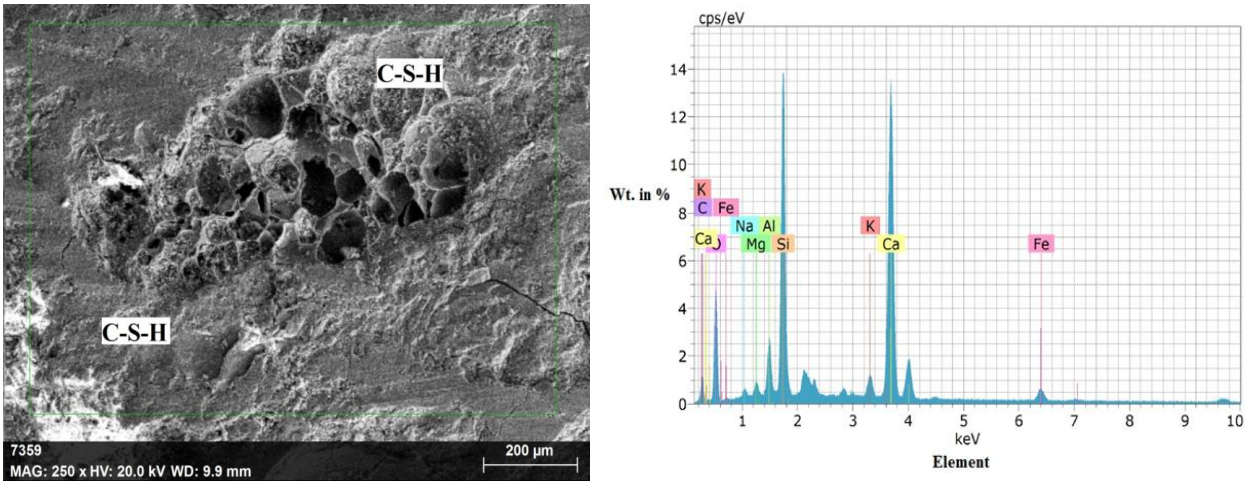


Figure 11 Microstructure of C–S–H gel in MN25 mix with EDS elemental analysis

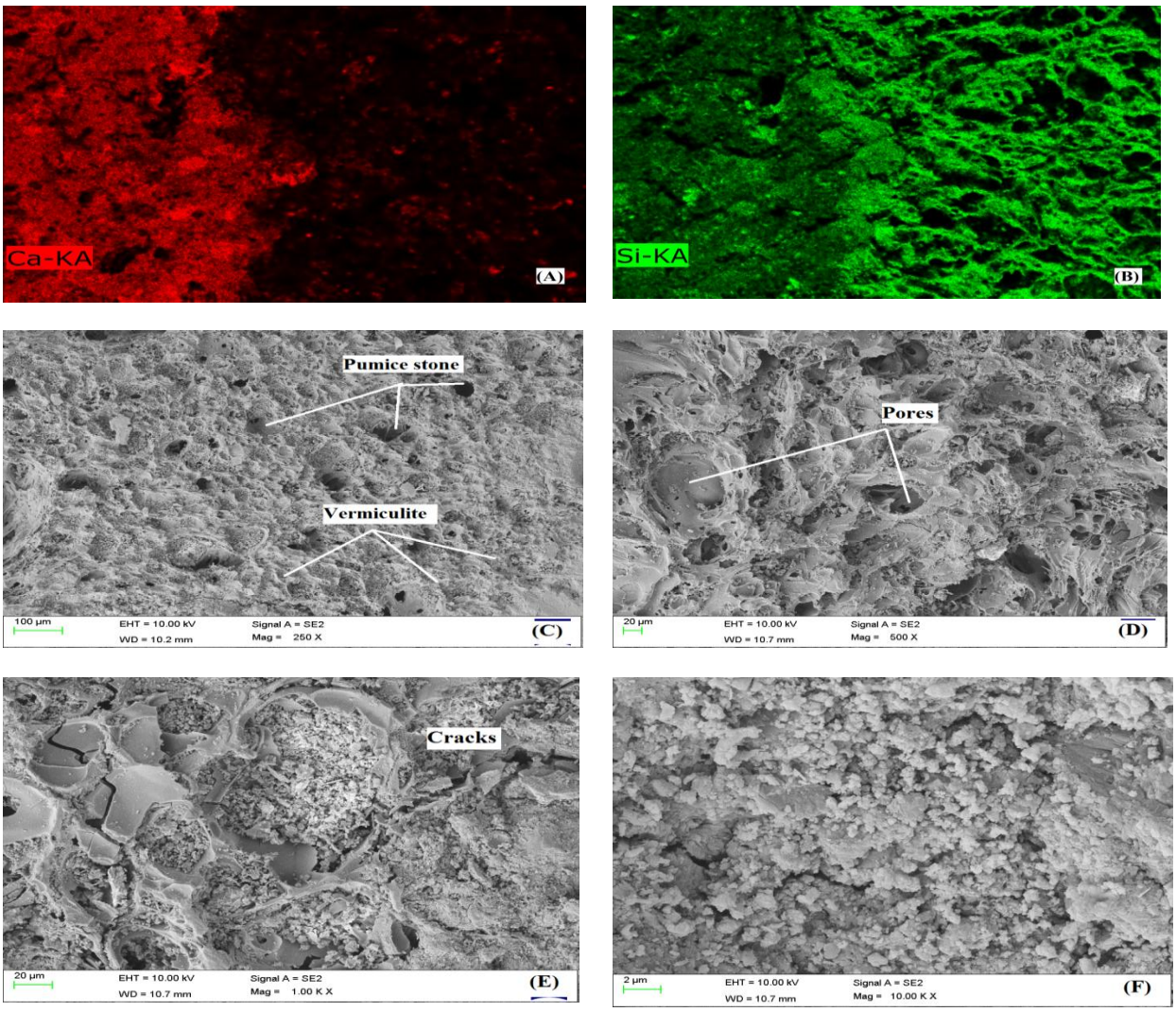


Figure 12 After-test SEM morphology of MN25 LWC showing surface texture and microstructural changes

5. Discussion

5.1 Overall result analysis

The results indicate a complex correlation between the void ratio of LWC mixtures, the CS of LWC mixtures, and the overall performance of mixtures. Surprisingly, the mix with highest void ratio, MN4, was found to be stronger, which shows that an intermediate air content together with balanced mix composition can enhance structural integrity without compromising on the lightweight characteristics. The low-ratio mixtures, e.g. MN5, MN10, and MN27 were not strength compliant, thereby indicating that excessively dense mixtures may hinder strength development. This proves that void ratio is not the only determinant of performance; aggregate dispersion and micro-silica concentration are also significant determinants. The importance of mix composition is further established by the data on water absorption. Trial-2 mixes containing micro-silica also exhibited much lower values (ranging between 12 to 2%), due to the densifying effect of micro-silica, but Trial 1 mixing with M-sand had higher water absorption. The constant low absorption values in Trial 3 enhanced its durability. However, the MN25 mixture in Trial-3 (2.7% absorption of water) did not comply with the required CS. This means that low porosity increases durability with no structural adequacy. The difference in density between fresh and cured concrete was also an important factor. Although reduced density may be useful to reduce dead load, when not balanced properly, might affect strength adversely. Its performance in terms of strength requires further optimization, but the lowest densities of Trial 3

qualify it as an ideal choice in situations that demand low weight.

The importance of the balanced mix proportions in LWC is supported by the CS results of all tests. With moderate proportions of vermiculite and pumice producing high strength, CS increased in Trial 1 in the following order: MN1 > MN2 > MN5 > MN6. Trial-2 showed low CS with early mixes (MN9, MN10) due to poor packing of its matrix, but MN12 had the highest strength due to its optimum micro-silica and pumice concentration. The MN16–MN24 had excessively used LWAs, which weakened strength. Due to a combination of materials, Trial 3 showed the highest results as MN31 (17.65 MPa) was the best, followed by MN32. The results of these studies show clearly that the micro-silica to aggregates ratio is selected precisely to increase the strength and overall performance of concrete significantly.

The STS results prove the fact that mix proportions are significant to performance. The combination of cement, pumice stone, vermiculite and micro-silica had the ideal ratio to enable MN12 to achieve the maximum STS in Trial-2. The same value of STS (0.55 N/mm^2) was observed in mixes like MN10 and MN13, but in mixes like MN22 to MN24, the value was lower due to high ratios of voids in the mixes due to the high number of LWAs. Trial-3 indicated that there was a gradual increase in the STS with the highest value recorded by MN31 due to better matrix packing.The usage of micro-silica, which results in micro-cracks, is probably what caused the decline in MN32. These findings highlight the necessity of optimal material ratios for increased tensile strength. Due to the addition of micro-silica, which improved matrix bonding and decreased porosity, FS considerably improved in Trial-3. Due to its weakness and porosity, pumice stone alone decreased FS in previous tests. With an FS of 2.84 N/mm^2, MN31 outperformed the other eight mixes, closely followed by MN32. MN25's reading of 1.28 N/mm² was identical to Trial-1 maximum. MN31 > MN32 > MN30 > MN29 > MN28 > MN27 > MN26 > MN25 is the FS sequence for Trial-3.

5.2 Comparative study of CS and STS relationship

The present study conducted a comparative analysis of the STS results obtained experimentally with those predicted using empirical formulas reported in prior research studies. Specifically, three well-established formulas (*Table 5*) were employed for this comparison: $f_{sp} = 0.55\ (f_{ck})^{0.5}$[37], $f_{sp} = 0.301\ (0.8\ f_{ck})^{0.65}$ [38], and $f_{sp} = 0.19\ (f_{ck})^{0.75}$[39]. These formulas, derived from extensive prior research, are frequently used to estimate the STS of concrete based on its CS (f_{ck}).

Table 5 Formulas were used to estimate the STS of concrete

Concrete type	STS (f_{sp})
LWC	$f_{sp} = 0.55\ (f_{ck})^{0.5}$[37]
	$f_{sp} = 0.301\ (0.8\ f_{ck})^{0.65}$ [38]
	$f_{sp} = 0.19\ (f_{ck})^{0.75}$[39]

A very interesting and noteworthy observation of the study is that there is a progressive growth in the values of the STS in the various trial mixes. Trial-1 (MN1), Trial 2 (MN12), and Trial 3 (MN31) exhibited the best STS value of 1.24 MPa [37], 1.80 MPa [37] and 2.31 MPa [37], respectively, which means that tensile performance indeed improved with the development of the mix design. This has been occasioned by the systematic change in mix compositions especially addition and proportioning of additives like microsilica, pumice stone and vermiculite, which are known to affect the microstructure and bonding in concrete matrix. It is probable that the role of these materials was to enhance the densification of the matrix, decrease the internal voids, and increase transition zones of the interfaces, which all contribute to increased tensile strength. Moreover, it is also interesting to note that the experimentally determined STS values of all mixes were higher than the ones predicted by the existing empirical equations of past research [36–41]. This implies that the existing mix designs particularly MN31 have better performance features which cannot be entirely reflected through traditional prediction models and thus necessitating the use of revised or material specific models in the event of using such alternative materials in concrete.

The equation $f_{sp}=0.55\ (f_{ck})^{0.5}$ [37] yielded the highest values in prediction compared to the other two formulas, $f_{sp}=0.301\ (0.8\ f_{ck})^{0.65}$ [38] and $f_{sp}=0.19\ (f_{ck})^{0.75}$ [39]. Nonetheless, although the [37] equation had the best performance compared to the latter two, even experimental testing on the predictions of equation were not even close to the actual STS values, in all the concrete mix tests. It is this uniform underestimation that transpires in all three models which highlights their limited applicability in those cases where the contemporary formulations of concrete are considered. This difference between

simulation and the experimental values is significant and indicates that the empirical models are not only inaccurate to a significant degree, but also they can give conservative and therefore ineffective design assumptions, which can be applied to the modern types of concrete.

5.3 Comparative study of CS and FS relationship

The researchers in this study compared the FS of concrete with the results of their previous research. The evaluation was based on established formulae, probably the ones included in *Table 6*. The primary aim of this study was to evaluate the differences between the experimentally obtained FS values and the values expected on the basis of these formulas in the past.

Table 6 Formulas were used to estimate the FS of concrete

Concrete type	FS (f_b)
LWC	$f_b = 0.62\ (f_{ck})^{0.5}$ [37]
	$f_b = 0.81\ (f_{ck})^{0.5}$ [40]
	$f_b = 0.70\ (f_{ck})^{0.5}$ [41]

The highest experimental FS values of 1.83 MPa [40], 2.65 MPa [40], and 3.40 MPa [40] recorded during Trial-1, Trial-2 and Trial-3 respectively by the mix ID of MN1, MN12, and MN31 respectively. These are the highest FS measurements of every testing stage that indicates the performance of each mix of concrete. Another general tendency observed in all examined mixtures was that the FS values were steadily increasing with it, which is a good indication of the gradual improvement of the flexural behavior of the concrete as the mix design changed. The trend demonstrates the usefulness of the material changes including adding mineral admixtures and fiber reinforcements in enhancing FS. However, the traditional empirical models were significantly lower in terms of the values they predicted. Of the three equations that were used to estimate FS, the equation $f_b = 0.81\ (f_{ck})^{0.5}$ [40] resulted in the highest predictions. Nevertheless, this model too could not reflect the full development of the experimental results, which once again indicated the undervaluation tendency of traditional predictive methods, when used in the current concrete mixes of innovative additives and improved proportions.

A number of empirical models have been developed to predict the FS and STS of LWC as functions of its characteristic CS based on a survey of the literature. Based on the equations in *Tables 5* and *6*, a regression analysis was performed using experimental data from the current study in order to provide mathematical correlations that are realistic. A power function structure was used to model the relationships, and the strengths were represented as functions of f_{ck} with exponents and coefficients that were obtained empirically. Regression coefficients (R^2) of 0.97 [40], 0.98 [41], and 0.97 [42] have been reported in previous research, suggesting that 97%, 98%, and 97% of the variance in CS & STS performance. Similarly CS & FS relation R^2 of 0.97 [37], 0.97 [40], 0.97 [41] have been reported. The current study's coefficient (R) is 0.97 and R^2 is 0.97, both of which are in line with previous research findings. This implies that the existing findings about the substantial correlation between CS and STS are in accordance with and validate the body of existing literature. The empirical models consistently underestimate the concrete's true flexural performance, as evidenced by the fact that even the highest anticipated values from this formula failed to match the experimentally measured FS values.

5.4 Mathematical correlation of current research

To describe the correlation between CS and STS, the regression equation is STS=0.149xCS+0.983 (*Figure 13*). The high coefficient of determination (R^2 = 0.972) of this equation shows that the corresponding change in CS could explain approximately 97.2% of the variance in STS. A high R^2 value indicates that CS is a potent predictor of tensile performance in concrete materials and confirms the robustness and reliability of the model. This finds specific applications in the engineering field particularly in direct tensile testing where compressive testing is more widely used and less complex than direct tensile testing.

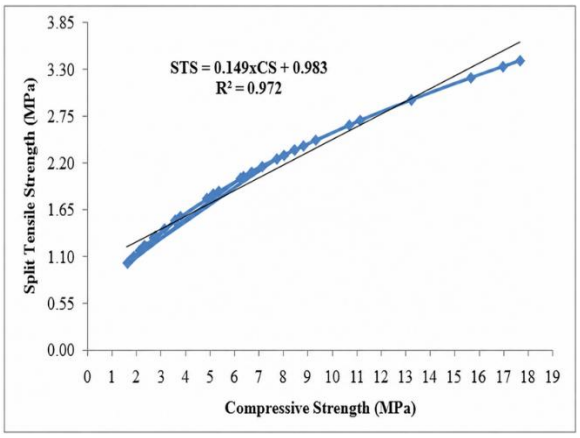


Figure 13 Correlation between CS and STS

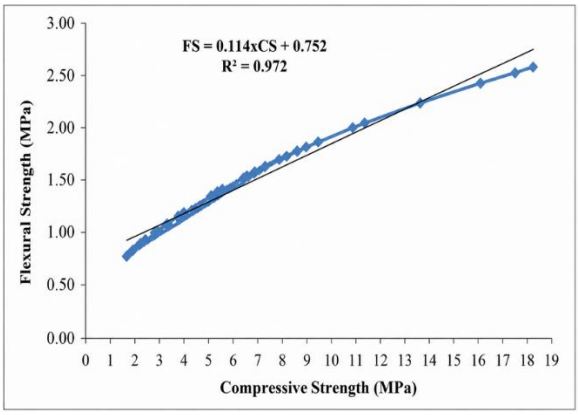


Figure 14 Correlation between CS and FS

On the same note, it has been established that CS and FS have a strong linear relationship. This relationship can be explained by the regression equation that was obtained as $FS = 0.114 \times CS + 0.752$ (*Figure 14*), and the corresponding regression equation also indicates the same high level of R^2, 0.972. The significance of CS as a fundamental predictor of the total mechanical behaviour can also be explained by the similarity in the coefficient of determination between the two models. Thus, it is possible to accurately estimate FS using CS data, which is crucial for evaluating the bending performance and fracture resistance of structural parts. The development of these relationships improves the effectiveness of material design and quality control in building procedures in addition to making it easier to forecast mechanical qualities. For structural engineers, material scientists, and researchers working on concrete technology and structural performance assessment, these models provide useful advantages by minimising the requirement for significant direct testing of tensile and flexural characteristics.

5.5 Study limitation

The short-term mechanical performance of LWC measured after 28 days of curing is considered to be the main subject of the current study. In spite of the fact that the results show that the CS and microstructural characteristics improved significantly, the long-term durability performance was not examined. Important durability parameters like chloride penetration resistance, sulfate attack resistance, freeze thaw durability, carbonation depth and long term behaviour of shrinkage were not evaluated. Besides, the experimental program was carried out in controlled laboratory conditions and performance in the field scale may differ owing to environmental and loading variations. Only a few mix proportions were taken into account in the study and further optimization beyond the selected mixes was not conducted. Thus, durability assessment, long-term performance observation, and validation through large-scale testing or real-life structural applications with the proposed LWC mixes should be considered in future studies to establish the practicality of such LWC mix fully.

A complete list of abbreviations is listed in *Appendix I*

6. Conclusion and future work

Based on the mechanical and microstructural evaluation of LWC incorporating vermiculite and pumice stone, several important conclusions can be drawn. The density of LWC decreased with increasing pumice content because of the highly porous and vesicular structure of pumice formed during rapid volcanic cooling. Among all the investigated mixes, the highest density was recorded for Mix MN5 in Trial-1 (1892.74 kg/m³), whereas the lowest density was obtained for Mix MN23 in Trial-2 (1178.37 kg/m³). As the pumice content increased, water absorption also increased due to its porous nature. However, the incorporation of a superplasticizer effectively reduced water absorption by improving the concrete's workability and matrix compactness. Furthermore, increasing the micro-silica content reduced the void ratio through enhanced formation of C-S-H gel, which filled internal pores and produced a denser cementitious matrix. The mechanical performance of the developed LWC improved significantly with the optimized material proportions. The maximum CS achieved in Trial-1 and Trial-2 was 5.11 N/mm² and 10.67 N/mm², respectively, both of which remained below the minimum requirement for structural LWC. In contrast, Mix MN31 satisfied the ASTM C330 requirements by achieving a CS of 17.65 N/mm², a density of 1438.48 kg/m³, a FS of 2.84 N/mm², and a STS of 1.63 N/mm². The superior performance of Mix MN31 is attributed to the synergistic effect of pumice, vermiculite, and micro-silica, which enhanced the microstructure by increasing C-S-H gel formation, reducing microcracks, improving aggregate interlocking, and providing internal curing, thereby producing a denser and stronger concrete matrix. The experimental results also demonstrated consistent improvements in tensile and flexural performance across all trials. The measured STS values ranged from 0.47 to 1.63 MPa, while the FS values ranged from 0.84 to 2.84 MPa. In all cases, the experimentally measured strengths were higher than

the corresponding predicted values, indicating that the optimized material combinations and the inclusion of advanced supplementary materials enhanced the mechanical behavior beyond that estimated by conventional prediction models. The observed difference of approximately 15% between the experimental and predicted values for both STS and FS suggests that existing empirical models require further refinement to accurately predict the performance of modern LWC containing vermiculite, pumice, and micro-silica. Overall, the reduction in porosity resulting from increased C-S-H gel formation significantly improved the compressive, flexural, and splitting tensile strengths. Among all the investigated mixtures, Mix MN31, with an optimal mix proportion of 1:0.5:2.5:0.15, exhibited the best overall performance by combining a low density (1438.48 kg/m³) with a CS of 17.65 N/mm², demonstrating its suitability as a structural LWC in accordance with ASTM C330.

Future research should focus on developing and experimentally validating advanced predictive models, including empirical formulations and machine learning approaches, specifically tailored for LWC incorporating LWAs, micro-silica, superplasticizers, and other modern admixtures. Comprehensive durability investigations should also be conducted to evaluate the long-term performance of the proposed concrete under aggressive environmental conditions, including freeze–thaw cycles, sulfate attack, carbonation, chloride ion penetration, and other degradation mechanisms. In addition, the combined effects of supplementary cementitious materials (SCMs), such as fly ash, nano-silica, and micro-silica, should be explored to optimize both mechanical and durability properties. Furthermore, future studies should investigate alternative generations of superplasticizers, curing admixtures, and internal curing agents to further reduce water absorption, minimize porosity, improve microstructural refinement, and enhance the overall performance and service life of structural LWC.

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Conflicts of interest
The authors have no conflicts of interest to declare.

Data availability
None.

Author's contribution statement
Ananthakumar Ayyadurai: Conceptualization, methodology, software, validation, investigation, resources, data curation, writing-original draft preparation. **Saravanan M M and Dineshkumar G**: Supervision, and review the article.

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Dr. Ananthakumar Ayyadurai received the Ph.D. degree in Civil Engineering from Anna University, Chennai, Tamil Nadu, India. He is currently an Associate Professor in the Department of Civil Engineering at Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India. His research interests include concrete technology, transportation engineering, composite structures, and special concretes.
Email: ananthaakumar7410@gmail.com



Dr. Saravanan M M received the Ph.D. degree in Civil Engineering from Anna University, Chennai, Tamil Nadu, India. He is currently serving as an Associate Professor and Head of the Department of Civil Engineering at Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India. His research interests include concrete technology, nanotechnology, transportation engineering, composite structures, and special concretes.
Email: saromms@gmail.com



Dr. Dineshkumar G received the Ph.D. degree in Civil Engineering from Anna University, Chennai, Tamil Nadu, India. He is currently serving as an Associate Professor and Head of the Department of Civil Engineering at Vaagdevi College of Engineering, Warangal, Telangana, India. His research interests include fibre-reinforced concrete, lightweight concrete, and green construction materials.
Email: gdkcivil@gmail.com

Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Society for Testing and Materials
2	CFRP	Carbon Fiber Reinforced Polymer
3	CS	Compressive Strength
4	EDS	Energy-Dispersive X-Ray Spectroscopy
5	EPS	Expanded Polystyrene
6	FESEM	Field Emission Scanning Electron Microscopy
7	FS	Flexural Strength
8	LOI	Loss On Ignition
9	LWA	Lightweight Aggregate
10	LWAC	Lightweight Aggregate Concrete
11	LWC	Lightweight Concrete
12	MN31	Mix number 31
13	MSW	Municipal Solid Waste
14	OPC	Ordinary Portland Cement
15	R^2	Regression coefficient
16	SCM	Supplementary Cementitious Materials
17	SEM	Scanning Electron Microscope
18	STS	Split Tensile Strength
19	R	Study's Coefficient
20	XRD	X-ray Diffraction