

Article

Structural Lightweight Concrete Containing Basalt Stone Powder

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Abstract: In spite of the demonstrated efficacy of basalt stone powder as a cost-effective and readily available additive in enhancing the mechanical properties and durability of ordinary-weight concrete, its application in Structural Lightweight Concrete (SLWC) remains unexplored. This study introduced a mixing design for SLWC incorporating Light Expanded Clay Aggregates (LECA) and basalt stone powder with a subsequent evaluation of its strength and durability characteristics. The experimental procedure involved creating various samples, considering differing proportions of cement, water, basalt stone powder, sand, LECA, superplasticizer, and aerating agent. The compressive strength and density of the 28-day-cured concrete specimens were determined. An optimal SLWC with a compressive strength of 42 MPa and a density of 1715 kg/m³ was identified. The flexural and tensile strength of the optimal SLWC exceeded those of ordinary-weight concrete by 6% and 3%, respectively. Further evaluation revealed that the optimal SLWC exhibited 1.46% water absorption and an electrical resistivity of 139.8 Ohm.m. Notably, the high porosity of LECA contributed to the low durability of SLWC. To address this, cost-effective external coatings of emulsion and fiberglass were applied to enhance the durability of the SLWC. Four coating scenarios, including one-layer bitumen, two-layer bitumen, three-layer bitumen, and three-layer bitumen with fiberglass, were investigated. The measurements of electrical resistance and compressive strength revealed that the use of three layers of emulsion bitumen and fiberglass improved the durability of the concrete by over 90% when the SLWC was exposed to severe chloride attack. Consequently, the durability of the SLWC with an external coating surpassed that of ordinary-weight concrete.

Keywords: structural lightweight concrete; basalt stone powder; LECA; high compressive strength; external coating; durability



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1. Introduction

Concrete, renowned for its high compressive strength, durability, and cost-effectiveness, stands as the foremost construction material [1]. Within the construction sector, lightweight concrete has gained prominence due to its advantageous characteristics, including low density, thermal insulation, and fire resistance [2]. For instance, Vandanapu et al. [3] conducted an investigation into the seismic performance of a six-story building constructed with lightweight concrete and showed that the application of lightweight concrete resulted in a notable reduction in both shear force and bending moments experienced by the structure subjected to the earthquake. A prevalent approach in the production of lightweight concrete involves incorporating different lightweight aggregates such as Light Expanded Clay Aggregate (LECA), scoria, and perlite into the concrete mixture design, substituting them for conventional aggregates such as sand and gravel [4]. Nevertheless, a laboratory study conducted by Rashad [5] demonstrated that employing lightweight aggregates in the concrete results in a reduction in its mechanical strength when compared with the properties of ordinary-weight concrete. In this regard, various researchers have undertaken numerous studies investigating the utilization of diverse additives aimed at enhancing the strength and durability properties of lightweight concrete. For instance, Karthik et al. [6] employed lime and LECA lightweight aggregate to fabricate structural lightweight concrete

with a density ranging from 1600 to 1960 kg/m³ and compressive strength ranging from 35 to 66 MPa. Shafigh et al. [7], Nadesan and Dinakar [8], Yasar et al. [9], and Tanyildizi and Coskun [10] demonstrated that the inclusion of fly ash as an additive can substantially enhance the compressive strength and durability of lightweight concrete. Numerous studies have demonstrated that using fibers made from various materials, including steel and polymer, in lightweight concrete enhance both its tensile and flexural strengths [11,12]. Keleştemur and Demirel [13] indicated that incorporating metakaolin at a proportion of 15% by weight of cement in lightweight concrete results in a notable enhancement of both the compressive strength and durability of lightweight concrete. Numerous studies have demonstrated that incorporating silica fume in lightweight concrete results in a substantial improvement in both compressive strength and durability [14–17]. Moreover, several studies have shown that the utilization of a superplasticizer in conjunction with silica fume in lightweight concrete can markedly enhance both compressive strength and workability, concurrently decreasing permeability and bolstering the overall durability of lightweight concrete [16].

Basalt stone stands out as a cost-effective natural additive that is abundantly accessible. Li et al. [18] and Uncik and Kmecova [19] indicated that using basalt stone powder in cement paste has a significant effect on the improvement of mechanical properties of cement paste. A multitude of researchers have demonstrated that incorporating basalt stone into ordinary-weight concrete, as a replacement for sand and gravel, enhances the mechanical and durability properties of the concrete [20–24]. Through extensive laboratory investigations, it has been proven that incorporating basalt stone powder into ordinary-weight concrete contributes to a notable reduction in the porosity of the Interfacial Transition Zone (ITZ) and consequently enhances both the compressive strength and overall durability of the concrete [25–27]. Furthermore, experimental investigations have demonstrated the substantial impact of incorporating basalt fibers on enhancing the strength and durability of ordinary-weight concrete [28–32]. In addition, multiple researchers have demonstrated that incorporating basalt fibers in the lightweight concrete results in enhanced tensile and bending strength for the concrete [33–35].

A review of the existing literature reveals that the permeability of lightweight concrete surpasses that of ordinary-weight concrete. Consequently, the durability of lightweight concrete to the penetration of external aggressive ions, such as chloride ions, is diminished when contrasted with that of ordinary-weight concrete. Accordingly, two distinct approaches, namely internal protection and external protection, are employed to mitigate the permeability of concrete. In the internal protection approach, diverse additives such as silica fume, fly ash, and nano-silica are incorporated into the concrete mix design, aiming to enhance the concrete's durability [36–38]. In the external protection approach, diverse coatings made from different materials such as polymer and bitumen are applied to the concrete surface to inhibit the ingress of deleterious substances into the concrete structure [39–42].

A literature review reveals that while basalt powder, an affordable and readily available additive, significantly enhances the compressive strength of ordinary-weight concrete and diminishes its permeability, its impact on the properties of structural lightweight concrete remains unexplored. Conversely, the use of bituminous coating, a proven external approach for enhancing the durability of ordinary-weight concrete, has not been applied to improve the durability of lightweight concrete. This research aims to address these two limitations by investigating the potential of basalt stone powder and bituminous coating to enhance both the mechanical and durability properties of structural lightweight concrete.

2. Methodology

The main objective of this study was reaching a proper mix design for Structural Lightweight Concrete (SLWC) with a 28-day compressive strength exceeding 35 MPa. Accordingly, this study included three distinct phases (Figure 1). In the first step, various mix designs, incorporating different materials such as basalt powder, cement, LECA lightweight aggregate, superplasticizer and air-entraining admixtures, sand, water, and silica fume

were evaluated. In this phase, the 28-day compressive strength and density of each mix design were assessed, leading to the identification of the optimal mix design (a balance between the highest compressive strength and the lowest density).

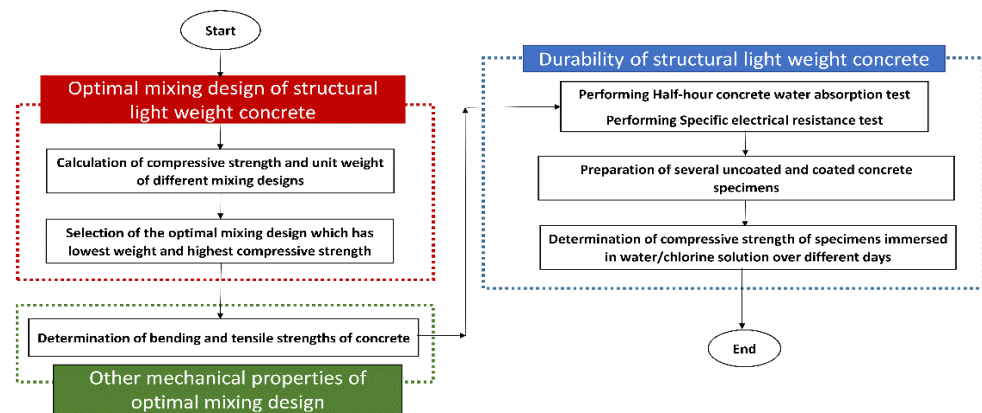


Figure 1. Methodology of this research.

In the second phase, additional mechanical properties of the optimal mix design of SLWC, including indirect tensile strength and bending strength, were assessed. The third phase of this study focused on evaluating the durability of the optimal mix design of SLWC and exploring the impact of external bitumen emulsion coating on its durability. Initial assessments involved a half-hour concrete water absorption test and specific electrical resistivity test to determine concrete permeability. Moreover, SLWC specimens (both uncoated and coated by bitumen) underwent immersion in water/chlorine solution, with subsequent monitoring of changes in specific electrical resistivity and compressive strength in response to chloride ion exposure over different days. The details of all phases (shown in Figure 1) are provided in the following sections.

3. Optimal Mixing Design of SLWC

In this stage, the optimal mixing design of SLWC with LECA aggregates and basalt stone powder was determined. In this regard, several ratios were considered for mixing cement, LECA, superplasticizer and air-entraining admixtures, sand, water, and silica fume. The density and compressive strength of each mixing design were measured to determine the optimal mixing design of SLWC. The details of this step are described in the following sub-sections.

3.1. Materials

This study employed Nahavand type II cement (CEM II/B-V 42.5), characterized by a density of approximately 3.15 g/cm^3 (Figure 2a). This type of cement includes about 75% Portland cement clinker content and about 25% pulverized fly ash content. Notably, this cement exhibits a slower initial setting time compared to type I cement, accompanied by reduced heat of hydration.

The investigation introduced silica fume to address several aspects of concrete enhancement (Figure 2b). This included filling concrete pores; diminishing permeability; amplifying compressive, tensile, and bending strengths; and ultimately augmenting concrete durability. Silica fume is derived from the cooling of exhaust gases in the electric arc furnace during ferroalloy melting. This silica fume boasts an exceptionally low specific weight ranging from 0.4 to 0.6 g/cm^3 , coupled with a substantial specific surface area falling within the range of 14 to $20 \text{ m}^2/\text{g}$.

Furthermore, this research pioneered the incorporation of basalt stone powder as a novel filler for structural lightweight concrete voids (Figure 2c). Basalt, a robust, black, fine-grained volcanic rock containing silica (SiO_2), represents a prevalent igneous rock type stemming from past volcanic activities, being particularly abundant in Iran. Noteworthy

for its granulation, the basalt stone powder particles surpass grade 18 sieve requirements, possessing a specific weight of 2.9 g/cm^3 and a hardness equivalent to 6 Mohs. All powder components used in this study are shown in Figure 2.

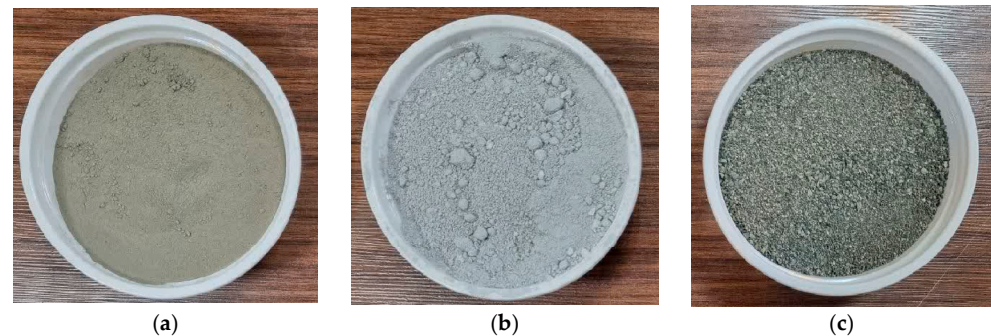


Figure 2. Powdered components of SLWC used in this study: (a) cement; (b) silica fume; (c) basalt stone powder.

Two types of aggregates including LECA and sand were used in this research. This study incorporated LECA, manufactured at the Saveh factory in Iran, within the formulation of SLWC. LECA light grains, derived from clay expansion in rotary kilns at temperatures surpassing 1200°C , exhibit characteristics such as low density, minimal thermal conductivity, and appropriate sound attenuation. Conventionally, LECA is employed in three distinct forms including fine, medium, and coarse aggregates with respective densities of 1120 , 880 , and 1040 kg/m^3 , respectively. Furthermore, the water absorption rates over 30 min and 24 h for the LECA aggregates were determined as 9.6 and 16.9 percent, respectively. In this research, the particle size distribution of LECA was prepared using sieve numbers 4, 8, 16, 30, 50, and 100 (Figure 3).

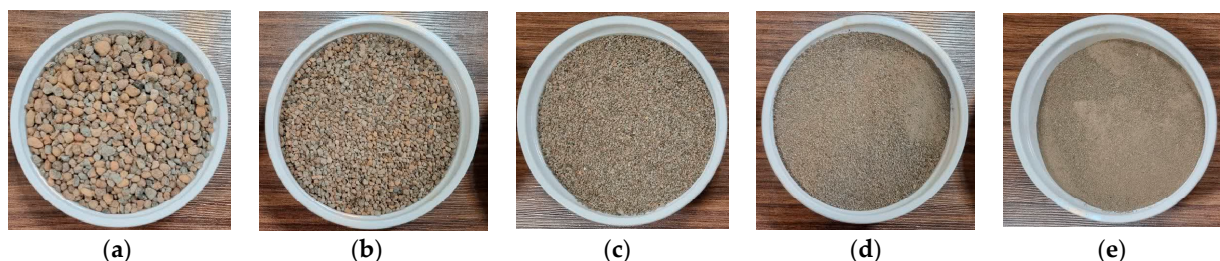


Figure 3. LECA remained on different sieves: (a) sieve #8; (b) sieve #16; (c) sieve #30; (d) sieve #50; (e) sieve #100.

According to the standards, the mesh sizes of sieve numbers 4, 8, 16, 30, 50, and 100 are 4.75, 2.36, 1.18, 0.6, 0.3, and 0.15 mm, respectively. Based on the mentioned sieve numbers (#4, #8, #16, #30, #50, and #100), the LECA aggregates used in all mix designs were split into five particle sizes. The first particle size category stood for the particle size between 4.75 and 2.36 mm. All aggregates in the first category passed through sieve number 4 and remained on sieve number 8. For the second category, all particles passed through sieve number 8 and remained on sieve number 16 (particle size between 2.36 and 1.18 mm). In addition, the sizes of all particles of LECA in the third category were between 1.18 and 0.6 mm. All particles of LECA in the third category passed through sieve number 16 and remained on sieve number 30. For the fourth and fifth particle size categories, the sizes of LECA were in ranges of 0.6 to 0.3 mm and 0.3 to 0.15 mm, respectively. In fact, all particles of LECA in the fourth category passed through sieve number 30 and remained on sieve number 50. Moreover, all particles of LECA in the fifth category passed through sieve number 50 and remained on sieve number 100 (Figure 3).

The sand utilized in this study underwent a meticulous washing process, resulting in a sand equivalent value of 2.75 and a fineness modulus of 3. Figure 4 shows the sand used in this study. The particle size distributions of LECA aggregate and sand used in this study are shown in Figure 5. Moreover, properties of granular materials (LECA and sand) used in this study are provided in Table 1. In this table, SSD stands for Saturated Surface-Dry. In addition, chemical compositions of LECA, basalt powder, cement, and silica fume provided by producers are presented in Table 2.



Figure 4. Sand used in this research.

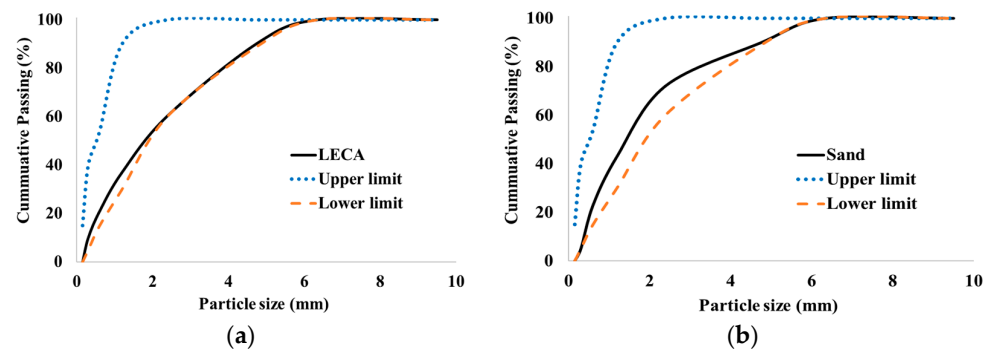


Figure 5. Particle size distribution for granular materials: (a) LECA; (b) sand.

Table 1. Properties of LECA and sand.

Properties	Material	
	LECA	Sand
Specific gravity	1.12	2.55
SSD specific gravity	1.31	2.61
Specific mass (g/cm^3)	1.39	2.69
Water absorption (%)	16.9	2.3

Table 2. Chemical compositions of materials (% by weight).

Chemical Compositions	LECA	Cement	Silica Fume	Basalt Powder
SiO_2 (%)	66.05	21.25	0.85	51
Al_2O_3 (%)	16.57	4.95	0.1	-
Fe_2O_3 (%)	7.1	3.19	0.2	-
CaO (%)	2.46	64.07	1.5	-
MgO (%)	1.99	1.20	0.2	-
TiO_2 (%)	0.78	-	-	-
P_2O_5 (%)	0.21	-	-	-

Table 2. *Cont.*

Chemical Compositions	LECA	Cement	Silica Fume	Basalt Powder
<i>MnO</i> (%)	0.09	-	-	-
<i>SiO₃</i> (%)	0.03	-	-	-
<i>Na₂O</i> (%)	0.69	0.38		-
<i>K₂O</i> (%)	2.69	0.63		-

This investigation was geared towards formulating structural lightweight concrete, targeting a 28-day compressive strength exceeding 35 MPa. To achieve this, meticulous attention was given to maintaining a low water/cement ratio. Consequently, a potent water-reducing additive was incorporated into the concrete mixing protocol. The study employed FOSROK 740 SR superplasticizer, the detailed specifications of which are outlined in Table 3. As per the manufacturer's guidelines for this high-performance admixture, the recommended dosage range was between 0.4 and 1.6 L per 100 kg of cement content.

Table 3. Properties of superplasticizer and air-entraining additives.

Properties	Material	
	Superplasticizer	Air-Entraining
Density (g/cm ³)	1.07 to 1.08	1.08 ± 0.05
Color	amber	transparent
Freezing point	sensitive to freezing	sensitive to freezing
Chloride content	<0.1%	None

Moreover, this study explored the incorporation of air-entraining additive in the SLWC mixing process as an approach to reduce concrete density. Aerating additives facilitate the formation of countless minuscule air bubbles, each measuring less than 0.5 mm. These bubbles exhibit distinct separation and homogeneous dispersion throughout the concrete matrix. The utilized aerating additive, sourced from Shimi Abadgaran Company (located in Tehran, Iran), aligns with the manufacturer's guidelines, advocating for a consumption rate of approximately 1 to 1.5% concerning the weight of cement. This strategy ensures the precise incorporation of air, optimizing the concrete's density while maintaining structural integrity. The properties of superplasticizer and air-entraining additives used in this study are provided in Table 3. Moreover, Figure 6 shows liquid admixtures utilized in this research.



(a)



(b)

Figure 6. Liquid admixtures utilized in this research: (a) superplasticizer; (b) air-entraining.

3.2. Mixing Design Ratios

This study drew upon prior research to establish specific criteria for material proportions with the dual aim of achieving optimal strength, durability, and minimal concrete density. The research explored the utilization of LECA, varying granulations, basalt stone powder, and superplasticizer and air-entraining admixtures in diverse combinations. The

LECA content ranged from 10% to 30% of concrete weight, with basalt stone powder constituting 33 to 36% by weight of cement and air-entraining additive being in the range of 1 to 1.5% by weight of cement [31,43,44]. Upon scrutinizing the existing literature, it is evident that the incorporation of LECA in concrete typically results in aggregate segregation [14]. To address this issue proactively, various additives, including superplasticizer, silica fume, and air-entraining agents, are commonly employed. These additives play a crucial role in mitigating the separation tendency observed with the concrete having LECA [6]. Accordingly, the details of 22 mixing designs for structural lightweight concrete considered in this study are provided in Table 4.

Table 4. Characteristics of different mixing designs considered in this study.

Mixing Design Number	Cement (kg)	Air-Entraining (%)	Silica Fume (kg)	Superplasticizer (kg)	Water (kg)	Water-to-Cement	Sand (kg)	Basalt Powder (kg)	LECA Lightweight Aggregate (kg)				
									2.36–4.75 mm	1.18–2.36 mm	0.6–1.18 mm	0.3–0.6 mm	0.15–0.3 mm
LWC1	495	0	55	11	176	0.36	485.1	220	-	207.9	-	-	-
LWC2	540	0	60	9	192	0.36	434.8	180	35.1	128.8	42.1	16.4	11.8
LWC3	495	0	55	6.6	154	0.31	553.6	165	35.1	128.8	42.1	16.4	11.8
LWC4	495	0	55	6.6	192	0.39	474.5	165	46.8	171.7	56.1	21.9	15.7
LWC5	495	0	55	6.6	154	0.31	453.6	165	55.1	148.8	62.1	36.4	31.8
LWC6	495	0	55	6.6	154	0.31	403.6	165	65.1	158.8	72.1	46.4	41.8
LWC7	495	1	55	6.6	154	0.31	453.6	165	55.1	148.8	62.1	36.4	31.8
LWC8	495	1	55	6.6	154	0.31	403.6	165	65.1	158.8	72.1	46.4	41.8
LWC9	495	1	55	6.6	154	0.31	353.6	165	35.1	128.8	42.1	16.4	211.8
LWC10	495	0	55	6.6	192	0.39	324.5	165	76.8	201.7	86.1	51.9	45.7
LWC11	495	1	55	6.6	192	0.39	324.5	165	76.8	201.7	86.1	51.9	45.7
LWC12	495	1.5	55	6.6	192	0.39	324.5	165	76.8	201.7	86.1	51.9	45.7
LWC13	495	1.5	55	6.6	192	0.39	324.5	-	76.8	201.7	86.1	51.9	45.7
LWC14	495	1.5	55	6.6	192	0.39	274.5	165	46.8	171.7	56.1	21.9	215.8
LWC15	495	0	55	6.6	192	0.39	274.5	165	86.8	211.7	96.1	61.9	55.7
LWC16	495	1	55	6.6	192	0.39	274.5	165	86.8	211.7	96.1	61.9	55.7
LWC17	495	1.5	55	6.6	192	0.39	274.5	165	86.8	211.7	96.1	61.9	55.7
LWC18	450	0	50	9	180	0.4	660.4	-	355.6	-	-	-	-
LWC19	450	1	50	9	200	0.44	510.4	-	505.6	-	-	-	-
LWC20	450	1.5	50	9	200	0.44	510.4	-	505.6	-	-	-	-
LWC21	450	1	50	9	180	0.44	510.4	-	505.6	-	-	-	-
LWC22	495	0	55	6.6	154	0.31	353.6	165	35.1	128.8	42.1	16.4	211.8

In the first mixing design, denoted as LWC1, LECA aggregates constitute approximately 10% of the concrete density while basalt stone powder accounts for 44% of the cement weight. Similarly, in the LWC2 and LWC3 mixing designs, LECA comprises 12% of the concrete density and the stone powder constitutes 33% of the cement weight. In LWC4, LECA usage increases to 17% of the concrete density, aligning with the 33% basalt stone powder content.

LWC5 and LWC6 exhibit a 33% basalt stone powder composition, with LECA levels at 18% and 22% of the total concrete density, respectively. Notably, design mixing numbers 1 to 6 omit air-entraining additives. LWC7 and LWC8 incorporate basalt stone powder and LECA, with a 1% air-entraining agent ratio to cement weight. LWC9 strategically increases the LECA content passing through a #100 sieve to diminish the porosity of ITZ, featuring 24% LECA, 33% basalt stone powder, and a 1% air-entraining additive ratio to cement weight. LWC10 and LWC11 maintain constant basalt stone powder levels while elevating LECA to 25% of the concrete density. LWC12 explores the impact of a 0.5% increase

in air-entraining agent quantity. Mixing design No. 13 replicates No. 12 but excludes basalt stone powder. In No. 14, stone powder levels persist while sand diminishes, and LECA fine grain and air-entraining agent quantities increase. LWC15, LWC16, and LWC17 sustain basalt stone powder levels while augmenting lightweight silica fume to reduce the concrete density. LECA's higher cost is acknowledged, cautioning against excessive use. Mixing plan No. 18 minimizes the water-to-cement ratio and eliminates air-entraining admixture and basalt stone powder, featuring 20% coarse LECA. The characteristics of mixing designs LWC19, LWC20, and LWC21 closely mirror those of LWC18, differing only in the LECA contents, which stand at 30%, 34%, and 33% by density of concrete, respectively. Notably, the LWC19, LWC20, and LWC21 mixing designs exclude basalt stone powder. The air-entraining admixture in these mixing designs varies at 1% and 1.5% by weight of cement. In LWC21, a noteworthy adjustment involves the reduction of the water-to-cement ratio. Additionally, the LWC22 mixing scheme targets further reduction in the porosity of the ITZ. To achieve this, the fine-particle LECA content has been augmented. In LWC22, the composition comprises 24% LECA lightweight aggregates by density of concrete (most of them are fine aggregates), 33% basalt stone powder by weight of cement, and 1% air-entraining admixture by weight of cement. It should be noted that in this study, different values of superplasticizer were used in different mix designs to achieve the same consistency in all mix designs.

3.3. Mixing Method of SLWC

Figure 7 provides a visual representation of mixing concrete and creating concrete specimens. According to the ASTM C-94 standard [45], the mixing process is initiated by introducing various dry materials including cement, silica fume, stone powder, and sand into a container with specified weights determined by the mixing design.

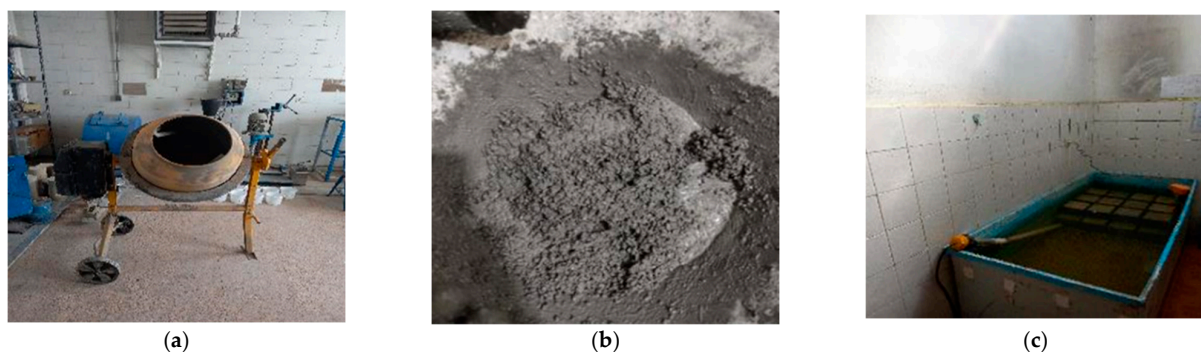


Figure 7. Different steps of mixing concrete and creating concrete specimens: (a) mixing chamber; (b) fresh concrete; (c) specimen curing.

Subsequently, the materials are thoroughly stirred. In the subsequent phase, water and liquid admixtures, including superplasticizer and air-entraining agents, are incorporated into the mixture. The operation of material mixing persists continuously from the initial blending until the concrete specimens are prepared. Fifteen to twenty minutes after the introduction of water to the stone and cement mixture, the first sampling occurs. Cube-shaped molds with 10 cm dimensions are employed to craft concrete specimens. Each sample is constructed by pouring concrete into the mold in two layers, each with a 5 cm thickness. To achieve the appropriate compaction in each concrete layer, the mixture is impacted 25 times using a metal rod. After 24 h staying in molds, the concrete specimens are extracted and immersed in basins filled with water to be cured for 28 days. Moreover, Figure 8 illustrates all concrete specimens investigated in this study.



Figure 8. A view of some concrete specimens investigated in this study.

3.4. Determination of Optimal Mixing Design of SLWC

In this section, the density and 28-day compressive strength of all mixing designs outlined in Table 4 were ascertained. All concrete specimens were taken out of water after 28 days; first, their densities were measured (Figure 9), and finally, their compressive strengths were measured (Figure 10) [46]. In this study, the compressive strength of concrete was determined based on the ASTM C39 standard [47]. It is noteworthy that three concrete specimens were prepared for each mixing design. It should be noted that the density and compressive strength determined for each mixing design represented an average magnitude of the values derived from three individual samples crafted for that specific mixing design. The 28-day compressive strength and density and their corresponding standard deviation values for all mixing designs are provided in Figure 11.



Figure 9. Determination of weight of concrete specimen.

In Figure 11, the standard deviations of compressive strengths obtained for all mixing designs are in the range of 0.8 to 1.16. For the densities of all mixing designs, the standard deviation is in the range of 1.01 to 1.15. This means that the standard deviations of compressive strength and density are relatively small for all cases. This shows the reliability of the performed tests. In light of the presented findings in Figure 11, the LWC1 mixing design demonstrates a compressive strength and density of 53.7 MPa and 1966 kg, respectively. Notably, while this mixing design achieves commendable compressive strength through relatively coarse LECA aggregates with a uniform gradation of 10% of the total concrete density, its overall density remains relatively high. Altering the mixing design by increas-

ing the LECA with continuous gradulation and reducing basalt stone powder by mixing designs numbers 2 and 3 results in a marginal change in density compared to that of LWC1.



Figure 10. Determination of compressive strength of concrete specimen.

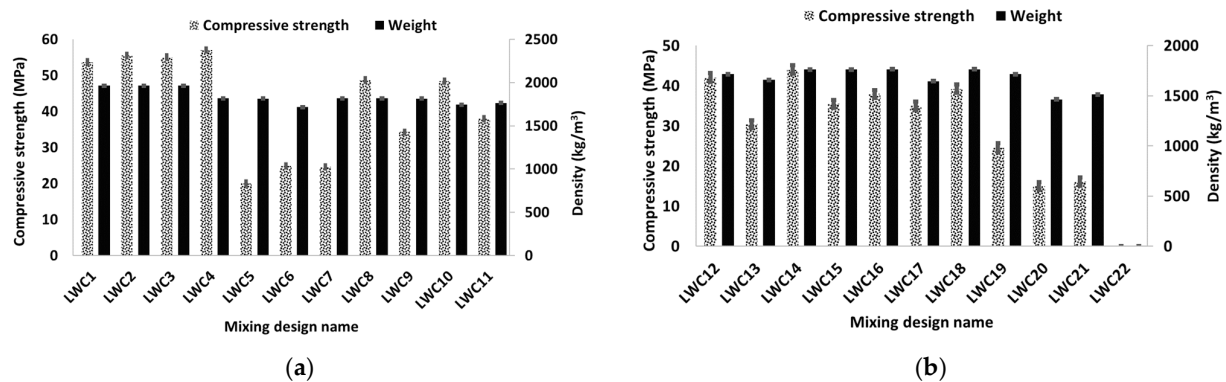


Figure 11. 28-day compressive strength and density values of all mixing designs: (a) No. 1 to 11; (b) No. 12 to 22.

However, the compressive strength experiences a slight increase, reaching approximately 55 MPa. Mixing design number 4, involving a reduction in the amount of sand, an increase in the amount of LECA, and a constant basalt stone powder amount compared to LWC2, significantly reduces the concrete density to about 1817 kg/m³. In contrast, its compressive strength reaches about 57 MPa. Further adjustments, such as reducing the water-to-cement ratio and sand content while keeping the basalt stone powder amount constant and increasing the amount of LECA in mixing designs 5 and 6, yield a density of 1850 kg/m³ and compressive strength of 20 MPa. This emphasizes that an excessive LECA increase, despite density reduction, can lead to a significant decrease in the compressive strength of the concrete. Comparing the densities and compressive strengths of mixing designs 7 to 9 with their corresponding values obtained for previous mixing designs reveals that while the use of air-entraining admixtures reduces concrete density, the amount of LECA, sand, and LECA gradation significantly influence the compressive strength and density of the concrete. In LWC10, reducing the amount of sand, increasing the amount of LECA with continuous gradation, and raising the water–cement ratio result in a density and compressive strength of 48.8 MPa and 1745 kg/m³, respectively. The impact of an air-entraining additive in varying quantities on the specifications of LWC10 is evident in mixing designs 11 and 12, leading to reduced density and compressive strength. Notably, an optimal 1.5% air-entraining admixture in LWC10 achieves a balanced reduction in density without a drastic decrease in compressive strength. Removing basalt stone powder in LWC12 is explored in LWC13, showing a 25% decrease in compressive strength. A review of the results obtained from mixing designs No. 15 to 17 reveals that altering LECA gradation to increase the amount of fine-grained and coarse-grained LECA leads to decreasing the compressive strength of concrete. However, incorporating 1.5% air-entraining

admixture in these mixing designs achieves a suitable reduction in concrete density. In LWC18, increasing the amount of sand and the water-to-cement ratio while using only coarse-grained LECA results in concrete with a compressive strength of 39.2 MPa and a density of 1766 kg/m³. Conversely, LWC22, with a high amount of fine-grained LECA and a water–cement ratio of 0.4, yields a very dry mixture, causing sample breakage after molding. A concise comparison of densities and compressive strengths across all mixing designs identifies LWC12, with a density of 1715 kg/m³ and a 28-day compressive strength of 42 MPa, as the optimal mixing design for structural lightweight concrete containing LECA and basalt stone powder. Figure 12 illustrates a visual representation of fractured concrete specimens subsequent to the completion of the compressive strength test.

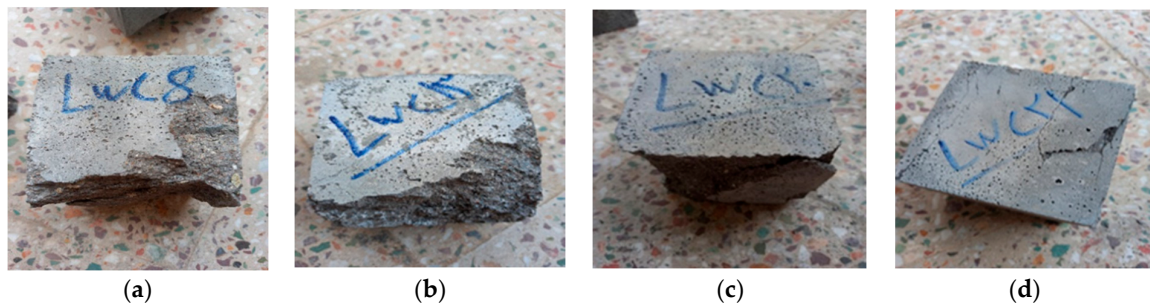


Figure 12. View of some fractured specimens: (a) LWC8; (b) LWC13; (c) LWC20; (d) LWC21.

3.5. Bending and Tensile Strength of Optimal SLWC

In this section, the tensile and bending strengths of the optimal structural lightweight concrete outlined by the optimal mixing design (LWC12) are evaluated. To determine tensile strength, a split (Brazilian) tensile strength test, as depicted in Figure 13 was conducted. This test indirectly measures the tensile strength of concrete.



Figure 13. A view of split (Brazilian) tensile strength.

According to the ASTM C496 standard apparatus [46], cylindrical concrete specimens with the standard dimension, cured for 28 days, were diametrically loaded along the length of the cylinder via a metal jack. To prevent stress concentration at the location of the application of external load and apply a uniform pressure to the concrete specimen, a wooden strip was interposed between the metal jack and the concrete sample. The applied load was incrementally increased at a steady rate until the cylindrical sample underwent a controlled split into two parts. It should be noted that three concrete specimens were prepared for this test. The tensile strength reported in this study was the average of tensile strength obtained from three individual samples.

In addition, a four-point bending test was carried out to measure the bending strength of the optimal SLWC (LWC12). This test was performed based on the ASTM C78 standard [48]. Accordingly, rectangular beam specimens with dimensions of 42 × 10 × 10 cm, featuring a square cross-section, were fabricated and cured for 28 days. As depicted in

Figure 14, two concentrated loads were applied at the midspan of the specimen, with a 40 mm distance between them. Loading was executed using a hydraulic jack with a capacity of 2000 kN, applying a loading rate of approximately 3 mm/min. The application of load persisted until the concrete sample underwent failure. It should be noted that three concrete specimens were prepared for this test. The bending strength reported in this study was the average of tensile strength obtained from three individual samples.



Figure 14. A view of four-point bending test.

To reach a better understanding of the bending and tensile strengths of the optimal SLWC (SLWC12) designed in this study, a comparison was made between the bending and tensile strengths of the optimal SLWC and an ordinary-weight concrete with a compressive strength of 40 MPa. In this regard, for each test, control concrete specimens were fabricated using ordinary-weight concrete exhibiting a compressive strength of 40 MPa and density of 2400 kg/m³. The characteristics of the mixing design of the control concrete specimens are presented in Table 5.

Table 5. Characteristics of mixing design of ordinary-weight concrete (control specimen).

Cement	Silica Fume	Superplasticizer	Water	Water-to-Cement Ratio	Sand	Gravel
495 kg	54 kg	13.5 kg	180 kg	0.4	960 kg	1440 kg

It is noteworthy that three control samples were prepared for each test. The tensile and bending strengths of the control specimens were calculated as the average values obtained from three individual control specimens. Table 6 presents the tensile and bending strengths and their corresponding standard deviation values for the optimal SLWC and control specimens. As provided in Table 6, while the compressive strengths of the optimal SLWC and normal-weight concrete were relatively the same, the tensile and bending strengths of the optimal SLWC were slightly higher than those of normal-weight concrete. Moreover, as illustrated in Table 6, the standard deviation obtained for all cases is in the range of 0.72 to 0.86, which is a relatively small value. This shows the reliability of the performed tests.

Table 6. Tensile and bending strengths of optimal SLWC and control specimens.

Type of Concrete	Tensile Strength (MPa)		Bending Strength (MPa)	
	Value	Standard Deviation	Value	Standard Deviation
Optimal SLWC	4.11	0.81	7.4	0.72
Normal-weight concrete	4.01	0.86	7	0.2

A comparison was made between the mechanical properties and density of the optimal SLWC developed in this study and those of lightweight concrete available in the literature to show advantages and disadvantages of the optimal SLWC developed in this research. In this regard, three different mixing designs of structural lightweight concrete developed in

three different previous studies (Refs. [6,49,50]) were considered. The details of different mixing designs are shown in Table 7.

Table 7. Details of different mixing designs derived from different references.

References for Mixing Design	Cement (kg)	Silica Fume (kg)	Air entraining (%)	Superplasticizer (kg)	Water (kg)	Sand (kg)	Stoen Powder (kg)	Different Size of LECA Aggregates in mm (kg)				
								2.36–4.75	1.18–2.36	0.6–1.18	0.3–0.6	0.15–0.3
This study	495	55	1.5	6.6	192	324.5	165	76.8	201.7	86.1	51.9	45.7
Ref. [6]	540	65	0	9	194	438.1	190	36.1	129.4	44.5	17.5	12.1
Ref. [49]	540	60	0	9	192	434.8	180	35.1	128.8	42.1	16.4	11.8
Ref. [50]	488.7	37.9	0	0	250	965	0	175.41	0	0	0	0

As presented in Table 7, the details of the optimal mixing design in this study were relatively the same as those proposed in Refs. [6,49,50]. LECA was used in all mixing designs. However, the particle size distribution considered for the LECA, using basalt stone powder and the utilization of air-entraining agent, was the main difference between the optimal mixing design of this study and those of other references. Table 8 shows the mechanical properties and densities of all mixing designs illustrated in Table 7. As presented in Table 8, while the bending and tensile strengths of optimal mixing design of this study were relatively the same as those of other mixing designs, the compressive strength of the optimal mixing design of this study was lower than those provided by Refs. [6,49].

Table 8. Comparison between mechanical properties and densities of different mixing designs.

References	Mechanical Strength (MPa)			Density (kg/m ³)
	Compressive	Tensile	Bending	
This study	42	4.11	7.04	1715
Ref. [6]	46	-	7	1833
Ref. [49]	47.6	4.27	6.76	1810 ± 23
Ref. [50]	20.48	-	-	1910

However, it should be noted that the density of the optimal mixing design of this study was lower than the densities of other mixing designs. Utilizing an air-entraining agent in the optimal mixing design of this study led to reducing the concrete density and compressive strength. On the other hand, the density and mechanical strength of the mixing design of Ref. [50] were significantly higher and lower than in other mixing designs, respectively. This was due to the fact that the water-to-cement ratio considered in Ref. [50] was significantly higher than those considered in other mixing designs. Moreover, the LECA particle size distribution considered in Ref. [50] was totally different from those in other references.

4. Durability of Optimal SLWC

The assessment of the durability of an optimal SLWC is detailed in this section, focusing on three key indicators: half-hour water absorption, concrete electrical resistivity, and the rate of change in compressive strength under chloride attack. The half-hour water absorption test [51] aimed to quantify the amount of water absorbed by the concrete within

a half-hour timeframe. Prior to the test, a 28-day-cured concrete specimen underwent a 24 h drying process in an oven with a temperature of 95 ± 5 °C. The weight of the dried specimen was recorded, followed by immersion in water for half an hour. Subsequently, the weight of the wet sample was measured, facilitating the calculation of the concrete's water absorption during the half-hour period. It should be noted that as the permeability of concrete increases, the amount of water absorbed by the concrete in this test increases and, consequently, the durability of concrete decreases.

An assessment of concrete electrical resistivity was conducted utilizing a bulk electrical resistivity test [43]. In this procedure, a 28-day-cured concrete specimen was positioned between two electrode probes, applying an Alternating Current (AC) (Figure 15). The electrode probes were made from aluminum. According to the procedure described in Ref. [43], the electrode probes (aluminum plates) were firmly attached to both sides of the specimen using a thin layer of cement paste. A specialized device promptly gauged the potential drop in voltage across the two electrode probes. The voltage was changed from 0 to 35 volts. For each voltage value, the corresponding electric current was measured using an ammeter. The electrical resistance of concrete (R) stood for the slope of the voltage–current line in Ohm. The electrical resistivity of concrete (ρ) was measured via the formula $R \times A/L$ (in Ohm.m), where A is the surface area of the specimen (0.01 m^2) and L represents the length of the specimen (0.1 m). The observed trend indicated that as the permeability of concrete decreases or the resistance of concrete against chloride ion attacks increases, there is a corresponding rise in concrete electrical resistivity, and consequently, the durability of concrete increases [43].

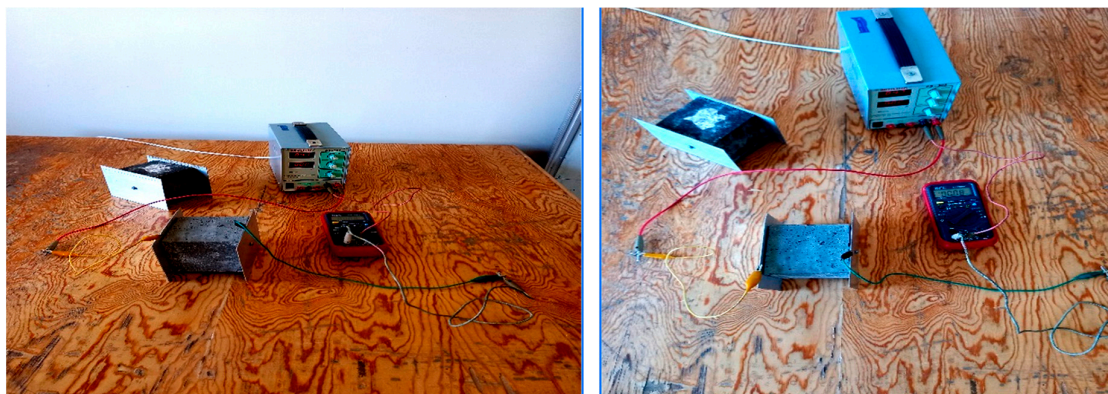


Figure 15. A view of bulk electrical resistivity test.

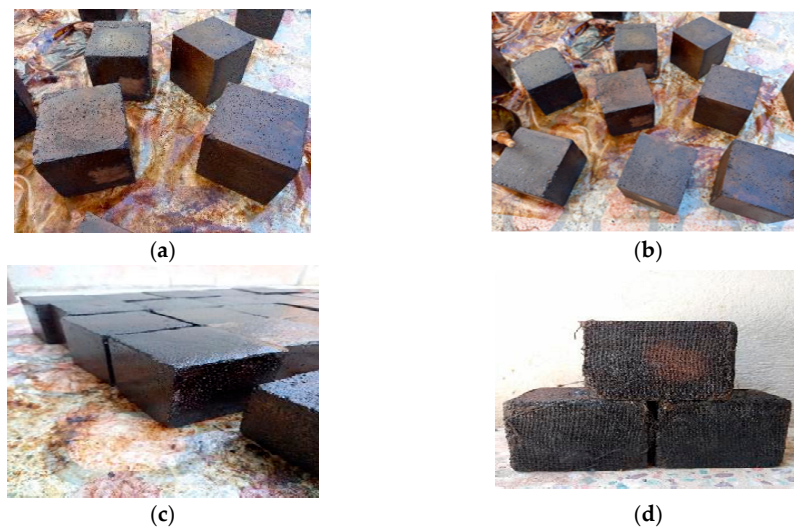
In the pursuit of a more comprehensive understanding of the durability of optimized SLWC, bulk electrical resistivity and half-hour water absorption tests were also conducted on control specimens, crafted from ordinary-weight concrete as detailed in the previous section. The results obtained from half-hour water absorption and electrical resistivity tests for both the optimal SLWC and ordinary-weight concrete are presented in Table 9. Moreover, the standard deviations of half-hour water absorption and electrical resistivity are provided in Table 9. The relatively small values of standard deviations provided in Table 9 show the reliability of the performed tests. As shown in Table 9, the half-hour water absorption and electrical resistivity of optimal SLWC exhibited a marked increase compared to those of ordinary-weight concrete. This disparity is attributed to the significantly higher porosity observed in the optimal SLWC in contrast to ordinary-weight concrete. The primary factor contributing to the elevated porosity of the optimal SLWC stems from the pronounced porosity exhibited by LECA. Consequently, this implies that the durability of the optimal SLWC is notably inferior to that of ordinary-weight concrete.

Table 9. Half-hour water absorption and electrical resistivity of concrete specimens.

Type of Concrete	Half-Hour Water Absorption (%)		Electrical Resistivity (Ohm.m)	
	Value	Standard Deviation	Value	Standard Deviation
Optimal SLWC	1.46	0.15	139.8	0.12
Normal-weight concrete	0.64	0.01	76.9	0.02

In light of the elevated permeability of the optimal SLWC, resulting in diminished durability against destructive external ion attacks, the effect of employing a cost-effective external coating on mitigating the permeability and enhancing the overall durability of the optimal SLWC was investigated in this section.

In this study, external coatings comprising Cationic Rapid Setting (CRS) emulsion bitumen manufactured by the Abadgaran Chemi company (located in Tehran, Iran), along with a fiberglass layer, were chosen for covering the external surfaces of concrete specimens. In this study, each layer of CRS emulsion bitumen coating was applied to the surface of a specimen using a paint brush. The fiberglass layer was only utilized to provide a denser and more integrated cover against chlorine ion penetration. The fiberglass layer used in this study had no significant effect on enhancing the compressive strength of the concrete specimen. Four types of external coatings, encompassing a single-layer emulsion bitumen coating, a two-layered emulsion bitumen coating, a three-layered emulsion bitumen coating, and, finally, a combination of a three-layered emulsion bitumen coating with a fiberglass layer (Figure 16), were considered.

**Figure 16.** Concrete specimens covered by different types of external emulsion bitumen coating: (a) one layer; (b) two layers; (c) three layers; (d) fiberglass; three-layered emulsion bitumen.

All 28-day-cured concrete specimens, fabricated from the optimal SLWC, underwent coverage with each type of external coating. The application of the external coating was omitted for ordinary-weight concrete samples. Subsequently, all specimens (coated and uncoated) were immersed in a chlorine water solution containing 380 ppm of chlorine, simulating an intense chloride attack. Following exposure durations of 28, 42, 56, and 70 days, the samples were extracted from the solution and their electrical resistivities and compressive strengths were measured. The electrical resistivity and compressive strength of all specimens are shown in Figures 17 and 18.

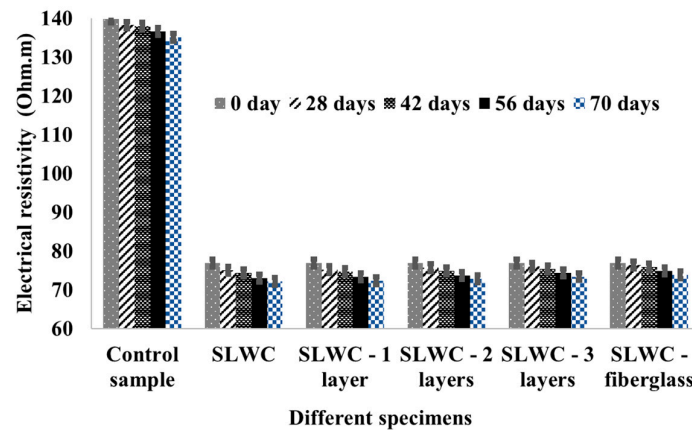


Figure 17. Effect of external cover on electrical resistivity of concrete.

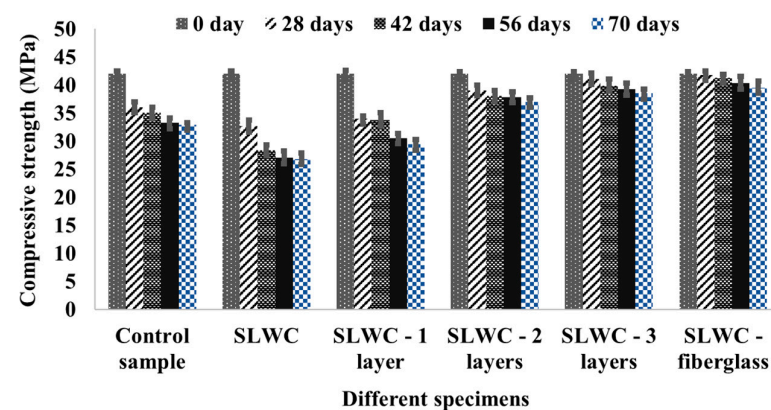


Figure 18. Effect of external cover on compressive strength of concrete.

As illustrated in Figure 17, the electrical resistivity of ordinary-weight concrete (control sample) was much higher than the electrical resistivity of SLWC in all cases. As shown in Figure 17, it was evident that the electrical resistivity of ordinary-weight concrete (control sample), characterized by its low permeability, experienced a marginal decrease of approximately 4% after 70 days under intense chloride ion exposure. It is noteworthy that this reduction, while observed, did not signify a substantial deviation. An examination of the electrical resistivity in various scenarios of SLWC, both with and without external coating, reveals that the presence of external coating, regardless of its type, exerts minimal influence on the alteration of concrete's electrical resistivity. This observation underscores the inherent nature of concrete, where its electrical resistivity remains relatively unaffected by external coatings.

According to Figure 17, with an escalation in the duration of chlorine ion exposure, a reduction in electrical resistivity becomes evident across all concrete specimens. In essence, irrespective of the concrete type (lightweight or ordinary-weight), augmenting the concentration of chloride ions introduced into the concrete results in a reduction in its electrical resistivity. Moreover, the standard deviation of electrical resistivity for all cases is in the range of 0.12 to 1.2, which is relatively small. This shows the reliability of the performed tests. Figure 18 illustrates the impact of diverse external coatings on the fluctuation of compressive strength and its standard deviation in concrete subjected to chloride attack. As depicted in this figure, while the compressive strength of all specimens remained consistent prior to chlorine exposure (0 days), the penetration of chlorine ions into the concrete induced a decrease in its compressive strength.

As shown in Figure 18, the standard deviation of compressive strengths measured for all cases was in the range of 0.36 to 1.41. The relatively small standard deviations of compressive strength for all cases showed the reliability of the performed experiments. As

the duration of chlorine ion infiltration increased, the compressive strength of the concrete was diminished in all cases. A review of the literature shows that when concrete is exposure to severe chloride attack, the compressive strength of concrete significantly decreases due to the chemical reaction between concrete and chloride ions [52,53]. For instance, calcium oxide (CaO) is a principal ingredient of cement [54]. When chloride ions penetrate concrete, chlorine ions (cl) react with calcium oxide (CaO) to form calcium chloride (CaCl₂). The formation of calcium chloride in the hardened concrete leads to decreases in its compressive strength [54]. This issue has been proved through microscopic experiments [54].

Notably, for concrete specimens without any external coating (control specimen and SLWC cases), this reduction is substantial. Conversely, the application of additional external coatings on lightweight concrete corresponds to a diminished decrease in compressive strength. For instance, in the case of SLWC featuring a single external coating layer (SLWC—one layer), the reduction rate in chloride ion attack resistance after 70 days is approximately 40%. In contrast, for SLWC endowed with three external coatings (SLWC—three layers), this reduction is around 9%. Notably, the compressive strength of SLWC, featuring both two-layer and three-layer external coatings as well as fiberglass (SLWC—one layer, SLWC—two layers, and SLWC—fiberglass cases), surpasses that of ordinary-weight concrete (control sample) following a 70-day exposure to chloride ions. This means that the application of an appropriate external coating to the surface of SWLC results in a reduction in the ingress of chloride ions, thereby enhancing the concrete's durability in corrosive environments.

5. Conclusions

A review of previous studies highlights the proven efficacy of basalt stone powder as a cost-effective and readily available additive, enhancing the mechanical properties and durability of normal-weight concrete. However, its application in Structural Lightweight Concrete (SLWC) remains largely unexplored. Accordingly, in this study, the 28-day compressive strength and density values of various concrete mix designs, incorporating basalt powder, were investigated to establish an optimal mix design for SLWC, achieving a 28-day compressive strength exceeding 35 MPa. Different materials such as Lightweight Expanded Clay Aggregates (LECAs), cement, superplasticizer, air-entraining admixtures, sand, water, and silica fume were incorporated in the mix designs. Also, the durability SLWC was investigated through a half-hour concrete water absorption test and specific electrical resistance test. The main findings of this study were as follows:

- An excessive increase in the amount of LECA, despite reducing concrete density, led to a significant decrease in compressive strength.
- An optimal 1.5% aerating additive achieved a balanced reduction in concrete density without a drastic decrease in compressive strength.
- A mix design with a density of 1715 kg/m³ and a 28-day compressive strength of 42 MPa was deemed an optimal mix design of SLWC.
- The indirect tensile and bending strengths of the optimal SLWC were determined as 4.11 and 7.4 MPa, respectively.
- The half-hour water absorption and electrical resistivity of optimal SLWC were 1.46% and 139.8 Ohm.m, respectively.
- Regardless of the concrete type (lightweight or ordinary-weight), augmenting the concentration of chloride ions led to a reduction in electrical resistivity and compressive strength.
- The application of additional external coatings on lightweight concrete corresponded to a diminished decrease in compressive strength, demonstrating that the durability of SLWC with an external coating surpassed that of normal-weight concrete.

In this study, through several macroscopic experiments, the effect of basalt powder on the mechanical properties and durability of lightweight concrete was investigated. However, the influence of basalt powder on the microscopic structure of lightweight concrete was neglected in this study and is required to be investigated in future studies. The findings obtained from future microscope-based studies will provide a deep understanding of the

effect of basalt powder on the structure and inherent behavior of lightweight concrete. The findings of microscopic tests help researchers in producing more accurate interpretations of the results obtained from macroscopic experiments.

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