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Effect of Mineral Additives on the Durability of Self-Compacted Lightweight Concrete Made with LECA

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Abstract

This study investigates the effects of incorporating various mineral additives on the durability characteristics of self-compacted lightweight concrete manufactured with Light Expanded Clay Aggregate (LECA). The research evaluates the performance of different mineral additives including lime powder (LP), marble dust (MD), fly ash (FA), and granulated quartz (GQ) at varying proportions (10%, 20%, and 30% of cementitious materials). Comprehensive durability assessments were conducted through multiple testing regimes including resistance to sulfate attack, chloride attack, freeze-thaw cycles, water permeability, and water absorption. The results demonstrate that the incorporation of mineral additives significantly enhances the durability properties of LECA concrete. Marble dust at 20% shows superior performance against sulfate attack with only 12.21% reduction in flexural strength compared to 17.62% for the control mix. Granulated quartz at 10% exhibits excellent resistance to chloride attack, while fly ash demonstrates progressively improved resistance to both sulfate and chloride attacks with increasing percentages up to 30%. The incorporation of 20% marble dust results in a 60% reduction in water permeability, while 30% fly ash concrete shows a remarkable 40.18% decrease in water absorption compared to the control mix. All LECA concrete samples maintain chloride and sulfate content within acceptable limits according to industry standards. The findings establish that the strategic incorporation of mineral additives, particularly marble dust and fly ash, substantially enhances the durability characteristics of self-compacted lightweight concrete, making it suitable for applications in aggressive environmental conditions.
Keywords: Self-compacted lightweight concrete, Light Expanded Clay Aggregate (LECA), mineral additives, marble dust, fly ash, lime powder, granulated quartz, durability, sulfate attack, chloride attack, freeze-thaw resistance, water permeability, water absorption, sustainable construction materials.

1. Introduction

Concrete is one of the most widely used construction materials worldwide, with ongoing research efforts aimed at enhancing its performance and sustainability [1]. The development of specialized concrete types, such as self-compacted lightweight concrete (LW-SCC), represents a significant advancement in concrete technology, offering benefits such as reduced dead load, improved thermal insulation, enhanced workability, and reduced energy consumption during transportation and handling [2-4]. Light Expanded Clay Aggregate (LECA) has emerged as a promising lightweight aggregate for producing structural lightweight concrete, offering a favorable balance between density reduction and strength retention [5-8].

Despite the advantages offered by LW-SCC, concerns regarding its durability in aggressive environments remain a significant challenge [9-10]. Concrete structures are frequently exposed to deterioration mechanisms such as sulfate attack, chloride penetration, freeze-thaw cycles, and water ingress, which can compromise their long-term performance and service life [11-12]. The inherent porosity of lightweight aggregates, including LECA, potentially increases the vulnerability of lightweight concrete to these degradation processes [13-15].

The incorporation of supplementary cementitious materials and mineral additives has been recognized as an effective approach to address durability concerns in conventional concrete [16-18]. These materials can modify the microstructure of the cementitious matrix, reduce permeability, and enhance resistance to chemical attacks. However, the specific effects of different mineral additives on the durability characteristics of self-compacted lightweight concrete manufactured with LECA remain inadequately investigated [19-21].

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This research aims to comprehensively assess the influence of four distinct mineral additives—lime powder, marble dust, fly ash, and granulated quartz—at varying proportions (10%, 20%, and 30% by weight of cementitious materials) on the durability performance of LECA-based self-compacted lightweight concrete. The study evaluates resistance to sulfate attack, chloride penetration, freeze-thaw cycles, water permeability, and water absorption, providing valuable insights into the durability enhancement mechanisms and optimal additive proportions for specific environmental conditions.

The findings of this study contribute to the advancement of knowledge regarding the durability of LECA-based self-compacted lightweight concrete and provide practical guidance for engineers and researchers seeking to develop durable lightweight concrete formulations for challenging environmental conditions. The results support the sustainable utilization of industrial by-products as mineral additives in concrete, aligning with global efforts to reduce the environmental footprint of construction materials.

2. Materials and Methods

2.1 Materials

2.1.1 Cement and Silica Fume

Ordinary Portland cement (CEM I 42.5N) conforming to BS EN 197-1 was used as the primary binder in all concrete mixtures. The cement had a specific gravity of 3.15 and a standard consistency water requirement of 26%. Silica fume with a specific gravity of 2.2 and a maximum particle size passing through a 45 μm sieve was incorporated at 10% replacement of cement by weight to enhance the cohesiveness and strength of the lightweight self-compacted concrete.

2.1.2 Aggregates

Natural siliceous sand with a specific gravity of 2.68 and a fineness modulus of 3.012 was used as fine aggregate. Light Expanded Clay Aggregate (LECA) with a bulk density of 0.89 t/m³, specific gravity of 0.99, and water absorption of 18.64% was employed as the lightweight coarse aggregate. The particle size distribution of both fine and coarse aggregates conformed to the requirements specified in ASTM C33.

2.1.3 Mineral Additives

Four types of mineral additives were investigated in this study:

1. Lime Powder (LP): A by-product from limestone quarries with a specific gravity of 2.7 and a fineness of 68% (percentage retained on sieve No.325).

2. Marble Dust (MD): A waste material from marble processing industries with a specific gravity of 2.4 and a fineness of 44.8%.

3. Fly Ash (FA): A Class F fly ash with a specific gravity of 2.13 and a fineness of 14%.

4. Granulated Quartz (GQ): Ground silica with a specific gravity of 2.8 and a fineness of 1.0%.

The chemical compositions and physical properties of these mineral additives are presented in Table 1.

Table 1. Properties of the mineral additives used in the study

Property	Lime Powder	Marble Dust	Fly Ash	Granulated Quartz
Physical state	Powder	Powder	Powder	Powder
Appearance (color)	White	White	Grey	White
Specific gravity	2.7	2.4	2.13	2.8
Fineness (% retained on sieve No.325)	68	44.8	14	1.0
pH	8-9	8-9	8-9	11
Loss on ignition (L.O.I%)	45.11	36.02	5.34	1.01
Insoluble residue (IR%)	1.09	3.05	87.67	12.92
Sulfate content (SO_3)	1.6	1.16	1.94	1.6

2.1.4 Chemical Admixtures

A polycarboxylate-based high-range water-reducing admixture (superplasticizer) with a density of 1.087 and a solid content of 42.69% was used to achieve the required flowability of the self-compacting concrete mixtures without excessive water addition.

2.2 Mix Proportioning and Specimen Preparation

A total of fourteen concrete mixtures were designed and prepared for this investigation. Two control mixtures were established: (i) LECA C0 with 100% ordinary Portland cement, and (ii) LECA C1 with 90% ordinary Portland cement and 10% silica fume replacement. Twelve additional mixtures were prepared by incorporating the four mineral additives (LP, MD,

FA, and GQ) at three different proportions (10%, 20%, and 30% by weight of cementitious materials) as additives to the LECA C1 control mixture.
The mix proportions were designed to achieve a target compressive strength of 25 MPa at 28 days while maintaining self-compactability and a density below 1800 kg/m³. The water-to-cementitious materials ratio ranged from 0.34 to 0.40, adjusted according to the water demand of each mineral additive. Table 2 presents the mix proportions of all concrete mixtures investigated in this study.

Table 2. Mix proportions of LECA concrete mixtures

Mix Code	**Cement (kg/m³)**	**Silica Fume (kg/m³)**	**Water (kg/m³)**	**Sand (kg/m³)**	**LECA (kg/m³)**	**SP (kg/m³)**	**Mineral Additive Type**	**Percentage (%)**	**Weight (kg/m³)**
LECA C0	500	-	170	721	373.8	7.5	-	-	-
LECA C1	450	50	170	721	373.8	7.5	-	-	-
LECA LP10	450	50	187	721	373.8	7.5	Lime powder	10	50
LECA LP20	450	50	204	721	373.8	7.5	Lime powder	20	100
LECA LP30	450	50	221	721	373.8	7.5	Lime powder	30	150
LECA MD10	450	50	187	721	373.8	7.5	Marble dust	10	50
LECA MD20	450	50	204	721	373.8	7.5	Marble dust	20	100
LECA MD30	450	50	221	721	373.8	7.5	Marble dust	30	150
LECA FA10	450	50	187	721	373.8	7.5	Fly ash	10	50
LECA FA20	450	50	204	721	373.8	7.5	Fly ash	20	100
LECA FA30	450	50	221	721	373.8	7.5	Fly ash	30	150
LECA GQ10	450	50	187	721	373.8	7.5	Granulated quartz	10	50
LECA GQ20	450	50	204	721	373.8	7.5	Granulated quartz	20	100
LECA GQ30	450	50	221	721	373.8	7.5	Granulated quartz	30	150

Concrete specimens of various sizes were prepared according to the requirements of different durability tests. The fresh concrete was mixed in a laboratory pan mixer. First, the dry ingredients (cement, silica fume, mineral additives, fine aggregate, and coarse aggregate) were mixed for approximately 1 minute. Then, water mixed with the superplasticizer was gradually added while mixing continued for an additional 3 minutes. The fresh concrete was assessed for self-compactability through slump flow, T50, J-ring, L-box, and V-funnel tests according to EFNARC guidelines.
The concrete specimens were cast in steel molds, compacted using slight vibration to remove entrapped air, and covered with plastic sheets to prevent moisture loss. After 24 hours, the specimens were demolded and subjected to water curing at 20 ± 2°C for 28 days before durability testing.

2.3 Test Methods

2.3.1 Resistance to Salt Attack

The resistance to salt attack was evaluated for two salts: sodium sulfate (Na_2SO_4) and sodium chloride (NaCl), both at 20% concentration. The test was designed to simulate alternating exposure conditions: a temperate/humid period (22 ± 2°C with 80

± 5% relative humidity) for 12 hours, followed by a hot/dry period (43 ± 2°C with 25 ± 5% relative humidity) for 12 hours. This cycling was performed in a curing cabinet that allowed precise control of humidity and temperature.
Prism specimens measuring 40 × 40 × 160 mm were partially immersed in the salt solutions to a depth of 10 mm for 30 complete cycles. After completion of the exposure cycles, the specimens were tested for flexural strength, and the broken portions were used to determine compressive strength. The weight loss of specimens due to salt attack was also measured. For comparison, control specimens of the same size and mix proportions were immersed in distilled water under the same temperature and humidity conditions.

2.3.2 Freeze-Thaw Test

The freeze-thaw resistance was evaluated according to ASTM C666/C666M (Procedure B, rapid freezing and thawing in air). Prism specimens measuring 40 × 40 × 160 mm were subjected to cycles of freezing at -18 ± 2°C for 12 hours followed by thawing at 4 ± 2°C for 12 hours. A total of 30 freeze-thaw cycles were performed. After the exposure, the specimens were tested for flexural strength, compressive strength, and weight loss. The results were compared with those of control specimens maintained at normal laboratory conditions.

2.3.3 Water Permeability Test

The water permeability test was conducted according to BS EN 12390-8:2000. Cubic specimens measuring 150 × 150 × 150 mm were subjected to a water pressure of 0.5 MPa for 72 hours. After the exposure, the specimens were split in half, perpendicular to the face exposed to water pressure, and the maximum depth of water penetration was measured. Three readings were taken for each specimen, and the average value was reported.

2.3.4 Water Absorption Test

The water absorption test was performed according to BS 1881-122:2011. Prism specimens measuring 40 × 40 × 80 mm were oven-dried at 105 ± 5°C until reaching constant mass, then cooled to room temperature in a desiccator. The initial weight of each specimen was recorded, after which the specimens were immersed in water. The weight gain was measured after 30, 60, 90, and 120 minutes of immersion. The measured absorption was corrected using a factor of 0.64 to account for the specimen geometry, and the corrected absorption rate was calculated.

2.3.5 Determination of Chloride and Sulfate Content

The total soluble chloride and sulfate content in hardened concrete was determined according to the Egyptian Code of Practice (ECP 203-2020). Concrete samples weighing not less than 1 kg were crushed and milled to pass through a 150 μm sieve (No. 100). The chloride content was determined by chemical analysis and expressed as a percentage by weight of cement. Similarly, the sulfate content was determined and expressed as SO_3 percentage by weight of cement.

3. Results and Discussion

3.1 Effect of Sodium Sulfate on LECA Concrete Mixes

The exposure of concrete to sulfate-rich environments represents a significant durability concern, as sulfate ions can react with the aluminate phases in cement paste to form expansive products such as ettringite and gypsum, leading to deterioration of the concrete matrix. The results of the sulfate attack resistance test, including flexural strength, compressive strength, and weight loss, are presented and discussed in this section.

3.1.1 Flexural Strength

The flexural strength of concrete specimens after exposure to sodium sulfate solution for 30 cycles, compared with corresponding specimens immersed in water, is presented in Figure 1.

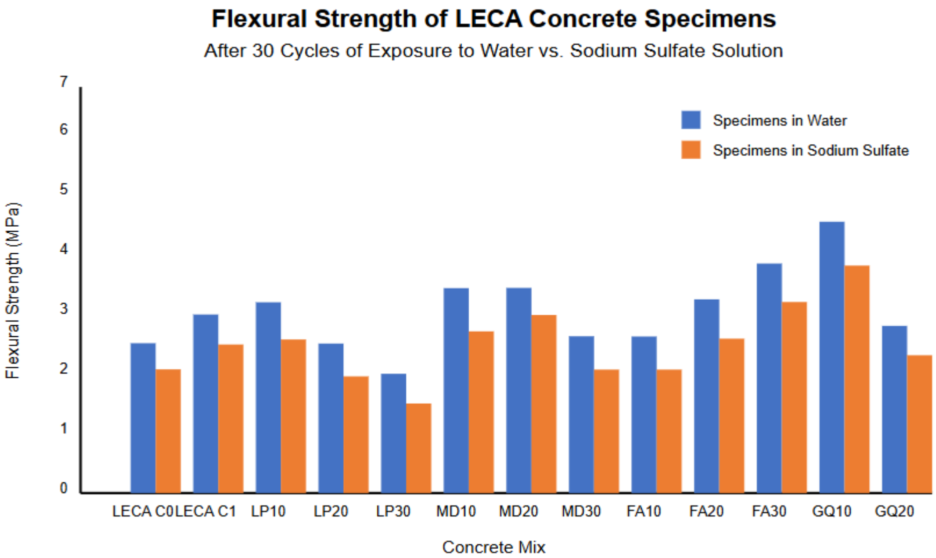

Figure 1: Flexural strength of LECA concrete specimens exposed to sodium sulfate solution

The results reveal that exposure to sodium sulfate solution led to a decrease in the flexural strength of all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited reductions in flexural strength of 17.62% and 17.63%, respectively, compared to the corresponding specimens immersed in water. This significant reduction indicates the vulnerability of conventional LECA concrete to sulfate attack.

The incorporation of mineral additives demonstrated varying degrees of effectiveness in mitigating sulfate-induced deterioration. The concrete mixtures containing lime powder at 10%, 20%, and 30% exhibited flexural strength reductions of 18.53%, 20.13%, and 23.37%, respectively. The increasing deterioration with higher lime powder content suggests that this additive does not provide enhanced resistance to sulfate attack and may actually exacerbate the problem at higher proportions.

In contrast, the concrete mixtures containing marble dust showed improved resistance to sulfate attack. The mixtures with 10%, 20%, and 30% marble dust exhibited flexural strength reductions of 19.48%, 12.21%, and 20.91%, respectively. Notably, the 20% marble dust mixture demonstrated the best performance among all mixtures, with the lowest reduction in flexural strength (12.21%). This enhanced performance can be attributed to the refinement of the pore structure and reduced permeability, which limit the ingress of sulfate ions into the concrete matrix.

The fly ash-containing mixtures showed reductions in flexural strength of 23.62%, 20.71%, and 19.95% for 10%, 20%, and 30% replacement levels, respectively. The improved performance with increasing fly ash content can be attributed to the pozzolanic reaction, which consumes calcium hydroxide (a compound vulnerable to sulfate attack) and forms additional calcium silicate hydrate (C-S-H), resulting in a denser and less permeable microstructure.

The mixtures containing granulated quartz at 10%, 20%, and 30% exhibited flexural strength reductions of 18.58%, 18.57%, and 18.25%, respectively. The relatively consistent performance across different replacement levels indicates that granulated quartz provides moderate resistance to sulfate attack, likely through its filler effect in the concrete matrix.

3.1.2 Compressive Strength

The compressive strength of concrete specimens after exposure to sodium sulfate solution, compared with corresponding specimens immersed in water, is presented in Figure 2. The specimens were tested for both the immersed part (directly exposed to the sulfate solution) and the saturated part (exposed to the solution through capillary suction).

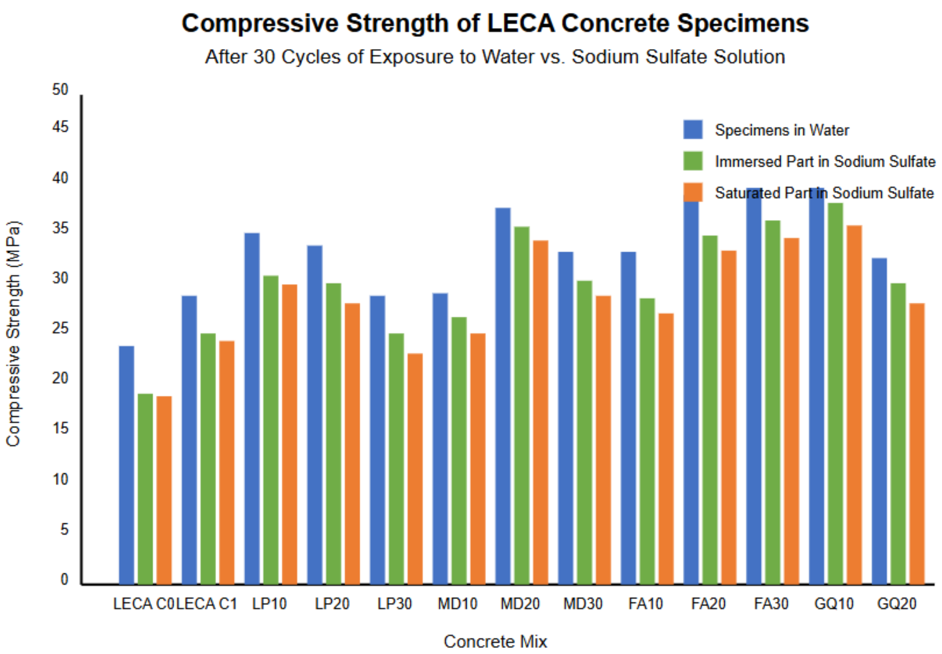

Figure 2: Compressive strength of LECA concrete specimens exposed to sodium sulfate solution

The compressive strength results reveal that exposure to sodium sulfate solution resulted in a reduction in compressive strength for all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited significant decreases in compressive strength. For LECA C0, the reduction was approximately 13.34% for the immersed part and 14.05% for the saturated part. For LECA C1, the reduction was 11.42% for the immersed part and 12.55% for the saturated part. These results underscore the vulnerability of conventional LECA concrete to sulfate attack and highlight the importance of incorporating suitable mineral additives to enhance sulfate resistance.

The concrete mixtures containing lime powder exhibited decreasing resistance to sulfate attack with increasing lime powder content. The reductions in compressive strength for the immersed parts were 9.38%, 13.54%, and 18.56% for mixtures with 10%, 20%, and 30% lime powder, respectively. The corresponding reductions for the saturated parts were 13.01%, 19.32%, and 25.22%. This trend suggests that higher lime powder content may exacerbate the susceptibility of concrete to sulfate attack, potentially due to the increased calcium hydroxide content, which is vulnerable to sulfate attack.

In contrast, the concrete mixtures containing marble dust demonstrated superior resistance to sulfate attack. The compressive strength reductions for the immersed parts were limited to 5.66%, 4.39%, and 5.23% for mixtures with 10%, 20%, and 30% marble dust, respectively. The corresponding reductions for the saturated parts were 12.01%, 6.42%, and 11.23%. The 20% marble dust mixture exhibited the best performance, with the lowest reduction in compressive strength. This enhanced performance can be attributed to the refinement of the pore structure and reduced permeability, which limit the ingress of sulfate ions and mitigate the formation of expansive reaction products.
The fly ash-containing mixtures showed improving resistance to sulfate attack with increasing fly ash content. The compressive strength reductions for the immersed parts were 13.02%, 11.90%, and 9.15% for mixtures with 10%, 20%, and 30% fly ash, respectively. The corresponding reductions for the saturated parts were 16.23%, 15.82%, and 14.50%. This trend aligns with the established understanding that fly ash contributes to enhanced sulfate resistance through its pozzolanic reaction, which reduces the calcium hydroxide content and forms additional C-S-H, resulting in a denser microstructure with reduced permeability.
The concrete mixtures containing granulated quartz exhibited moderate resistance to sulfate attack, with slight deterioration as the quartz content increased. The compressive strength reductions for the immersed parts were 4.38%, 5.71%, and 6.90% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The corresponding reductions for the saturated parts were 9.93%, 11.04%, and 12.51%. The relatively low reduction for the 10% granulated quartz mixture indicates its effectiveness in enhancing sulfate resistance, likely through its filler effect and contribution to pore refinement.
Across all mineral additives, the compressive strength reduction was generally more pronounced in the saturated parts compared to the immersed parts. This observation can be attributed to the cyclic exposure conditions, where the saturated parts experienced alternating wet-dry conditions, which have been shown to accelerate sulfate attack due to the concentration of sulfate ions during the drying phase.

3.1.3 Weight Loss

The weight loss of concrete specimens after exposure to sodium sulfate solution for 30 cycles, compared with corresponding specimens immersed in water, is presented in Figure 3.

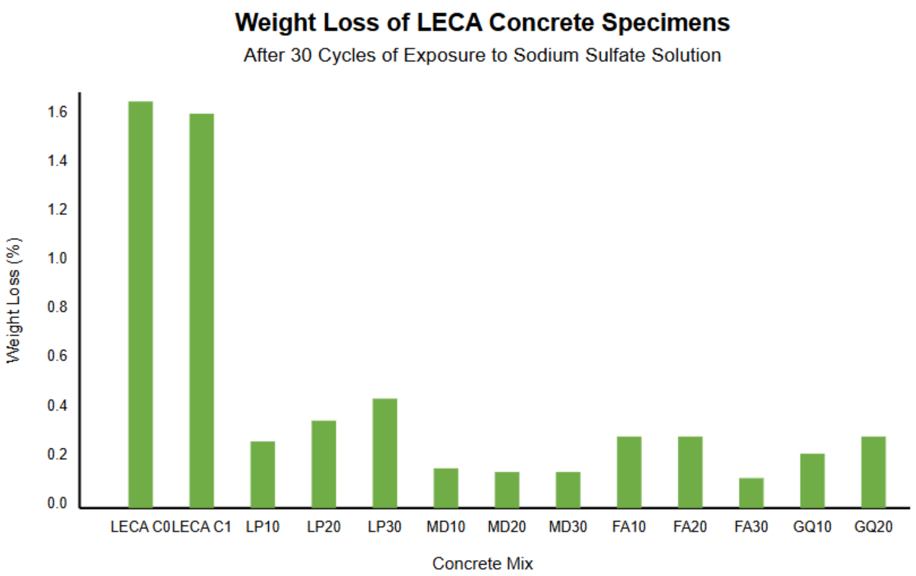

Figure 3: Weight loss of LECA concrete specimens exposed to sodium sulfate solution

The weight loss results provide valuable insights into the physical deterioration of concrete specimens exposed to sodium sulfate solution. The control mixtures (LECA C0 and LECA C1) exhibited the highest weight loss values, at 1.323% and 1.213%, respectively. This considerable weight loss indicates significant material degradation due to the formation of expansive reaction products and subsequent cracking and spalling.
The concrete mixtures containing lime powder demonstrated decreasing resistance to sulfate attack with increasing lime powder content, consistent with the trends observed for flexural and compressive strengths. The weight loss values were 0.359%, 0.457%, and 0.693% for mixtures with 10%, 20%, and 30% lime powder, respectively. While these values represent an improvement over the control mixtures, the increasing trend with higher lime powder content suggests diminishing returns beyond a certain replacement level.
The concrete mixtures containing marble dust exhibited the best resistance to sulfate-induced weight loss, with values of 0.157%, 0.123%, and 0.122% for mixtures with 10%, 20%, and 30% marble dust, respectively. The remarkably low weight loss, particularly for the 20% and 30% replacement levels, indicates the effectiveness of marble dust in mitigating physical deterioration due to sulfate attack. This superior performance can be attributed to the filler effect of marble dust, which reduces the permeability of the concrete and limits the ingress of sulfate ions.

The fly ash-containing mixtures showed improved resistance to weight loss with increasing fly ash content. The weight loss values were 0.389%, 0.392%, and 0.114% for mixtures with 10%, 20%, and 30% fly ash, respectively. The significant improvement at 30% fly ash content aligns with the established understanding that higher fly ash content contributes to enhanced sulfate resistance through pozzolanic reactions and pore refinement.

The concrete mixtures containing granulated quartz exhibited moderate resistance to weight loss, with values of 0.273%, 0.383%, and 0.548% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The increasing weight loss with higher quartz content suggests that an optimal replacement level may exist, beyond which the benefits of quartz addition diminish.

Overall, the weight loss results corroborate the findings from the flexural and compressive strength tests, highlighting the superior performance of marble dust and high-content fly ash mixtures in mitigating sulfate-induced deterioration.

3.2 Effect of Sodium Chloride on LECA Concrete Mixes

Chloride-induced deterioration represents a significant durability concern for concrete structures, particularly in marine environments and areas subject to deicing salts. The results of the chloride attack resistance test, including flexural strength, compressive strength, and weight loss, are presented and discussed in this section.

3.2.1 Flexural Strength

The flexural strength of concrete specimens after exposure to sodium chloride solution for 30 cycles, compared with corresponding specimens immersed in water, is presented in Figure 4.

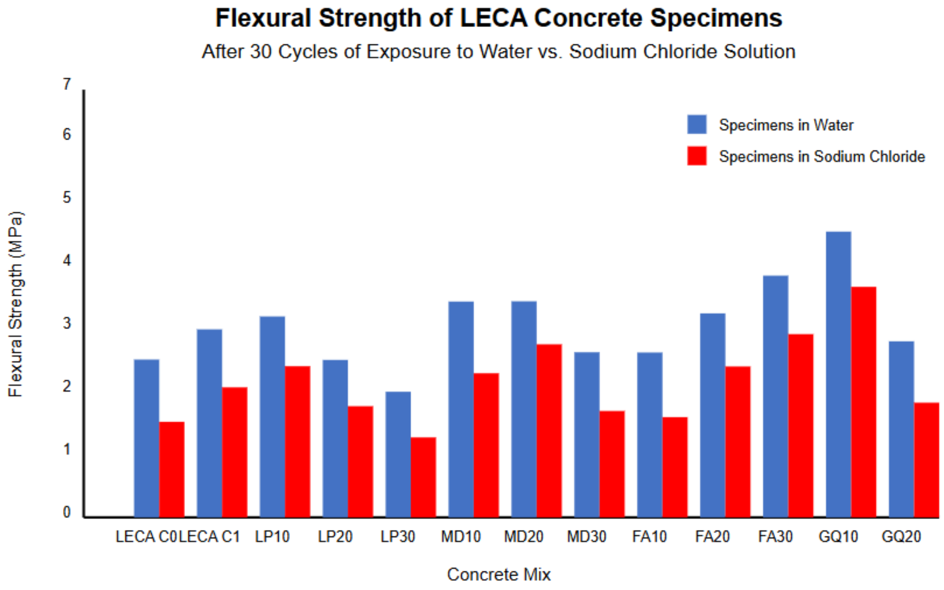

Figure 4: Flexural strength of LECA concrete specimens exposed to sodium chloride solution

The results reveal that exposure to sodium chloride solution led to a more pronounced decrease in flexural strength compared to sodium sulfate exposure for all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited substantial reductions in flexural strength of 29.5% and 26.44%, respectively, compared to the corresponding specimens immersed in water. This significant deterioration highlights the aggressive nature of chloride attack on concrete.

The concrete mixtures containing lime powder showed varying degrees of resistance to chloride-induced deterioration. The mixtures with 10%, 20%, and 30

The concrete mixtures containing lime powder showed varying degrees of resistance to chloride-induced deterioration. The mixtures with 10%, 20%, and 30% lime powder exhibited flexural strength reductions of 16.19%, 22.03%, and 28.64%, respectively. While the 10% lime powder mixture demonstrated significant improvement over the control mixtures, the increasing reduction with higher lime powder content suggests a threshold beyond which additional lime powder becomes detrimental to chloride resistance.

The marble dust-containing mixtures exhibited superior resistance to chloride attack compared to the control and lime powder mixtures. The flexural strength reductions were 20.64%, 15.52%, and 19.58% for mixtures with 10%, 20%, and 30% marble dust, respectively. The 20% marble dust mixture showed the best performance, with the lowest reduction in flexural strength. This enhanced performance can be attributed to the densification of the microstructure through the filler effect of marble dust, which reduces the permeability and restricts the ingress of chloride ions.

The fly ash-containing mixtures demonstrated progressively improving resistance to chloride attack with increasing fly ash content. The flexural strength reductions were 26.75%, 20.08%, and 16.62% for mixtures with 10%, 20%, and 30% fly ash, respectively. This trend aligns with established understanding that higher fly ash content contributes to enhanced chloride resistance through pozzolanic reactions, which refine the pore structure and increase the chloride binding capacity of the concrete.

The granulated quartz mixtures exhibited varying resistance to chloride attack. The flexural strength reductions were 14.79%, 21.07%, and 26.48% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The 10% granulated quartz mixture demonstrated the best performance among all mixtures, with the lowest reduction in flexural strength. However, the increasing deterioration with higher quartz content suggests an optimal replacement level, beyond which the benefits diminish.

3.2.2 Compressive Strength

The compressive strength of concrete specimens after exposure to sodium chloride solution for 30 cycles, compared with corresponding specimens immersed in water, is presented in Figure 5. The specimens were tested for both the immersed part (directly exposed to the chloride solution) and the saturated part (exposed to the solution through capillary suction).

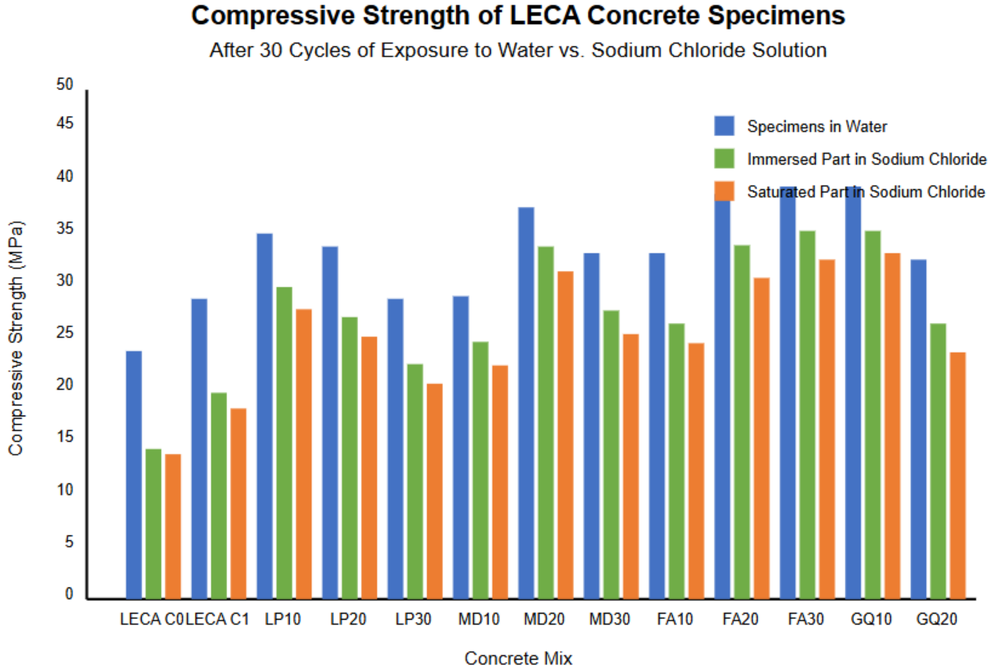

Figure 5: Compressive strength of LECA concrete specimens exposed to sodium chloride solution

The compressive strength results reveal that exposure to sodium chloride solution resulted in a more pronounced reduction in compressive strength compared to sodium sulfate exposure for all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited severe decreases in compressive strength. For LECA C0, the reduction was approximately 27.77% for the immersed part and 29.92% for the saturated part. For LECA C1, the reduction was 24.29% for the immersed part and 26.84% for the saturated part.

The concrete mixtures containing lime powder exhibited decreasing resistance to chloride attack with increasing lime powder content. The reductions in compressive strength for the immersed parts were 11.67%, 20.03%, and 24.46% for mixtures with 10%, 20%, and 30% lime powder, respectively. The corresponding reductions for the saturated parts were 14.14%, 21.41%, and 26.63%. While the 10% lime powder mixture demonstrated significant improvement over the control mixtures, the increasing reduction with higher lime powder content suggests a threshold beyond which additional lime powder becomes detrimental to chloride resistance.

The concrete mixtures containing marble dust demonstrated superior resistance to chloride attack compared to the control and lime powder mixtures. The compressive strength reductions for the immersed parts were 14.69%, 10.79%, and 15.9% for mixtures with 10%, 20%, and 30% marble dust, respectively. The corresponding reductions for the saturated parts were 16.38%, 12.82%, and 18.11%. The 20% marble dust mixture exhibited the best performance, with the lowest reduction in compressive strength. This enhanced performance can be attributed to the densification of the microstructure through the filler effect of marble dust, which reduces the permeability and restricts the ingress of chloride ions.

The fly ash-containing mixtures demonstrated progressively improving resistance to chloride attack with increasing fly ash content. The compressive strength reductions for the immersed parts were 19.49%, 13.63%, and 11.45% for mixtures with 10%, 20%, and 30% fly ash, respectively. The corresponding reductions for the saturated parts were 24.14%, 19.2%, and 15.09%. This trend aligns with established understanding that higher fly ash content contributes to enhanced chloride resistance through pozzolanic reactions, which refine the pore structure and increase the chloride binding capacity of the concrete.

The granulated quartz mixtures exhibited varying resistance to chloride attack. The compressive strength reductions for the immersed parts were 11.94%, 17.16%, and 21.18% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The corresponding reductions for the saturated parts were 13.36%, 20.27%, and 24.92%. The 10% granulated quartz mixture demonstrated the best performance, with the lowest reduction in compressive strength. However, the increasing deterioration with higher quartz content suggests an optimal replacement level, beyond which the benefits diminish.

Across all mineral additives, the compressive strength reduction was generally more pronounced in the saturated parts compared to the immersed parts. This observation can be attributed to the cyclic exposure conditions, where the saturated parts experienced alternating wet-dry conditions, which have been shown to accelerate chloride attack due to the concentration of chloride ions during the drying phase and the potential for repeated crystallization-dissolution cycles of sodium chloride.

3.2.3 Weight Loss

The weight loss of concrete specimens after exposure to sodium chloride solution for 30 cycles, compared with corresponding specimens immersed in water, is presented in Figure 6.

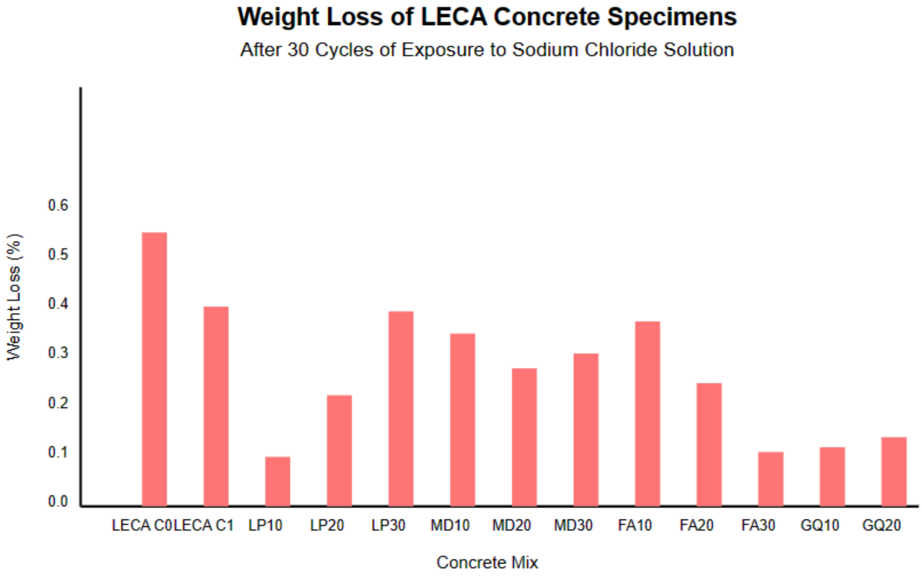

Figure 6: Weight loss of LECA concrete specimens exposed to sodium chloride solution

The weight loss results provide insights into the physical deterioration of concrete specimens exposed to sodium chloride solution. The control mixtures (LECA C0 and LECA C1) exhibited the highest weight loss values, at 0.556% and 0.404%, respectively. While these values are lower than those observed for sulfate exposure, they still indicate significant material degradation due to chloride attack.

The concrete mixtures containing lime powder demonstrated decreasing resistance to chloride-induced weight loss with increasing lime powder content. The weight loss values were 0.1%, 0.229%, and 0.395% for mixtures with 10%, 20%, and 30% lime powder, respectively. While these values represent an improvement over the control mixtures, the increasing trend with higher lime powder content suggests diminishing returns beyond a certain replacement level.

The concrete mixtures containing marble dust exhibited consistent and improved resistance to chloride-induced weight loss. The weight loss values were 0.354%, 0.284%, and 0.31% for mixtures with 10%, 20%, and 30% marble dust, respectively. Unlike the trend observed for sulfate exposure, the weight loss did not decrease consistently with increasing marble dust content. The 20% marble dust mixture demonstrated the best performance, with the lowest weight loss.

The fly ash-containing mixtures showed progressively improving resistance to weight loss with increasing fly ash content. The weight loss values were 0.387%, 0.256%, and 0.112% for mixtures with 10%, 20%, and 30% fly ash, respectively. The significant improvement at 30% fly ash content suggests that higher fly ash content contributes to enhanced chloride resistance, likely through pozzolanic reactions and pore refinement.

The granulated quartz mixtures exhibited varying resistance to weight loss. The weight loss values were 0.158%, 0.192%, and 0.385% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The superior performance of the 10% granulated quartz mixture, followed by a deterioration with increasing quartz content, suggests an optimal replacement level beyond which the benefits diminish.

Overall, the weight loss results corroborate the findings from the flexural and compressive strength tests, highlighting the superior performance of high-content fly ash mixtures and moderate-content marble dust mixtures in mitigating chloride-induced deterioration.

3.3 Effect of Freeze-Thaw Cycles on LECA Concrete Mixes

Freeze-thaw resistance is a critical durability parameter for concrete structures in cold regions, where repeated cycles of freezing and thawing can lead to progressive deterioration. The results of the freeze-thaw resistance test, including flexural strength, compressive strength, and weight loss, are presented and discussed in this section.

3.3.1 Flexural Strength

The flexural strength of concrete specimens after exposure to 30 freeze-thaw cycles, compared with corresponding specimens maintained at normal laboratory conditions, is presented in Figure 7.

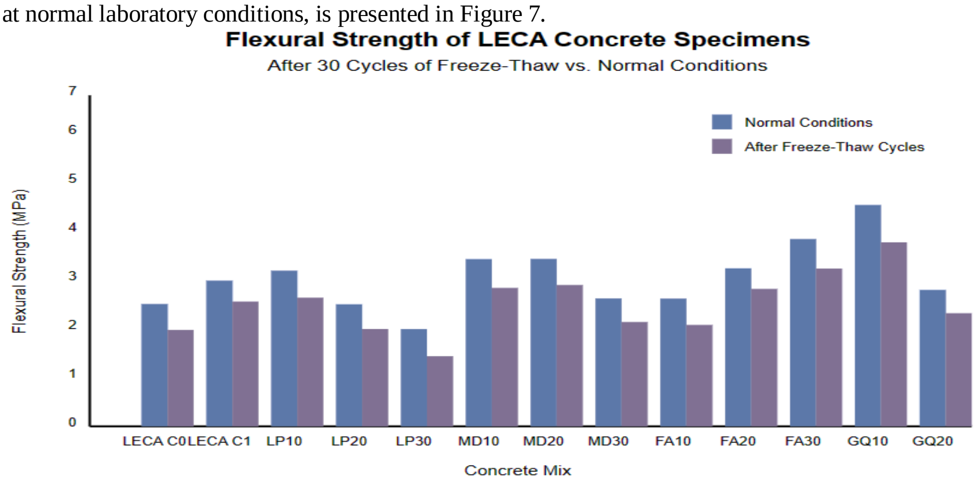

Figure 7: Flexural strength of LECA concrete specimens exposed to freeze-thaw cycles

The results reveal that exposure to freeze-thaw cycles led to a decrease in the flexural strength of all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited significant reductions in flexural strength of 20.99% and 18.98%, respectively, compared to the corresponding specimens maintained at normal laboratory conditions. This substantial reduction indicates the vulnerability of conventional LECA concrete to freeze-thaw damage.

The concrete mixtures containing lime powder showed varying degrees of resistance to freeze-thaw damage. The mixtures with 10%, 20%, and 30% lime powder exhibited flexural strength reductions of 11.19%, 15.25%, and 16.58%, respectively. The superior performance of the 10% lime powder mixture suggests an optimal replacement level, beyond which additional lime powder becomes detrimental to freeze-thaw resistance.

The marble dust-containing mixtures demonstrated excellent resistance to freeze-thaw damage. The flexural strength reductions were 15.99%, 11.64%, and 15.02% for mixtures with 10%, 20%, and 30% marble dust, respectively. The 20% marble dust mixture exhibited the best performance, with the lowest reduction in flexural strength. This enhanced performance can be attributed to the refinement of the pore structure, which can accommodate the expansive forces generated during ice formation.

The fly ash-containing mixtures showed progressively improving resistance to freeze-thaw damage with increasing fly ash content. The flexural strength reductions were 18.08%, 13.43%, and 11.97% for mixtures with 10%, 20%, and 30% fly ash, respectively. This trend is consistent with established understanding that higher fly ash content contributes to enhanced freeze-thaw resistance through pozzolanic reactions, which refine the pore structure and reduce the freezable water content.

The granulated quartz mixtures exhibited variable resistance to freeze-thaw damage. The flexural strength reductions were 11.81%, 15.00%, and 18.25% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The superior performance of the 10% granulated quartz mixture suggests an optimal replacement level, beyond which the benefits diminish.

3.3.2 Compressive Strength

The compressive strength of concrete specimens after exposure to 30 freeze-thaw cycles, compared with corresponding specimens maintained at normal laboratory conditions, is presented in Figure 8.

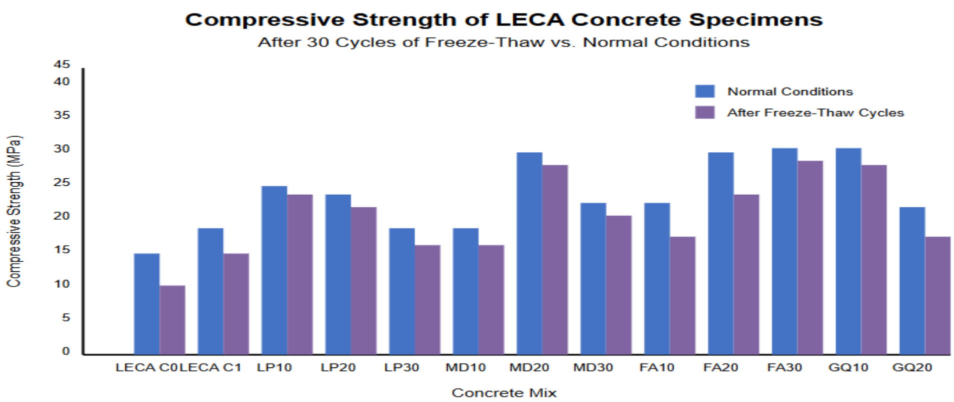

Figure 8: Compressive strength of LECA concrete specimens exposed to freeze-thaw cycles

The compressive strength results reveal that exposure to freeze-thaw cycles resulted in a reduction in compressive strength for all LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited significant decreases in compressive strength of 19.31% and 17.1%, respectively, compared to the corresponding specimens maintained at normal laboratory conditions. This substantial deterioration underscores the vulnerability of conventional LECA concrete to freeze-thaw damage.

The concrete mixtures containing lime powder demonstrated superior resistance to freeze-thaw damage compared to the control mixtures. The compressive strength reductions were 6.81%, 8.54%, and 11.54% for mixtures with 10%, 20%, and 30% lime powder, respectively. The increasing reduction with higher lime powder content suggests an optimal replacement level, beyond which additional lime powder becomes detrimental to freeze-thaw resistance.

The marble dust-containing mixtures exhibited excellent resistance to freeze-thaw damage, particularly at moderate replacement levels. The compressive strength reductions were 8.21%, 5.91%, and 8.24% for mixtures with 10%, 20%, and 30% marble dust, respectively. The superior performance of the 20% marble dust mixture, with a reduction of only 5.91%, indicates its effectiveness in mitigating freeze-thaw damage. This enhanced performance can be attributed to the refinement of the pore structure, which can accommodate the expansive forces generated during ice formation.

The fly ash-containing mixtures showed progressively improving resistance to freeze-thaw damage with increasing fly ash content. The compressive strength reductions were 19.3%, 15.43%, and 8.09% for mixtures with 10%, 20%, and 30% fly ash, respectively. This trend is consistent with established understanding that higher fly ash content contributes to enhanced freeze-thaw resistance through pozzolanic reactions, which refine the pore structure and reduce the freezable water content.

The granulated quartz mixtures exhibited varying resistance to freeze-thaw damage. The compressive strength reductions were 7.45%, 12.68%, and 17.31% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The superior performance of the 10% granulated quartz mixture suggests an optimal replacement level, beyond which the benefits diminish.

3.3.3 Weight Loss

The weight loss of concrete specimens after exposure to 30 freeze-thaw cycles, compared with corresponding specimens maintained at normal laboratory conditions, is presented in Figure 9.

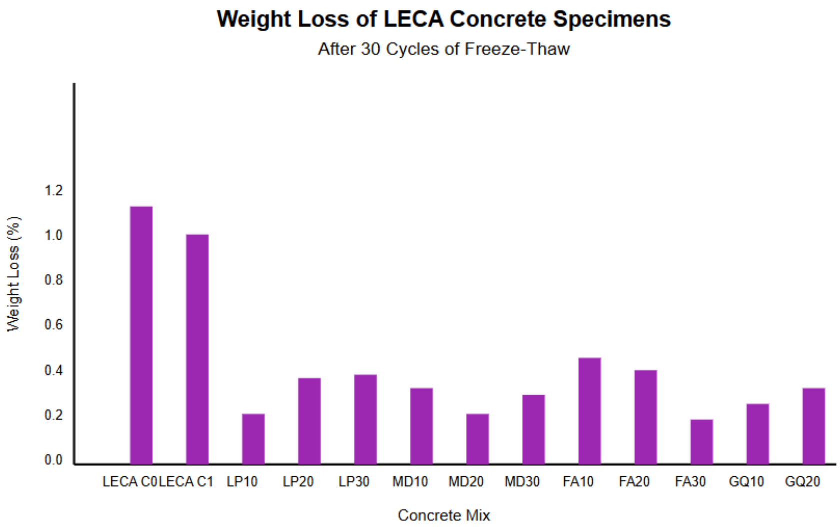

Figure 9: Weight loss of LECA concrete specimens exposed to freeze-thaw cycles

The weight loss results provide insights into the physical deterioration of concrete specimens exposed to freeze-thaw cycles. The control mixtures (LECA C0 and LECA C1) exhibited the highest weight loss values, at 1.079% and 0.944%, respectively. This significant weight loss indicates substantial material degradation due to the expansive forces generated during ice formation and thawing.

The concrete mixtures containing lime powder demonstrated superior resistance to freeze-thaw-induced weight loss compared to the control mixtures. The weight loss values were 0.226%, 0.573%, and 0.602% for mixtures with 10%, 20%, and 30% lime powder, respectively. The increasing weight loss with higher lime powder content suggests an optimal replacement level, beyond which additional lime powder becomes detrimental to freeze-thaw resistance.

The marble dust-containing mixtures exhibited varying resistance to freeze-thaw-induced weight loss. The weight loss values were 0.489%, 0.226%, and 0.444% for mixtures with 10%, 20%, and 30% marble dust, respectively. The superior performance of the 20% marble dust mixture, with a weight loss of only 0.226%, indicates its effectiveness in mitigating freeze-thaw damage. This enhanced performance can be attributed to the refinement of the pore structure, which can accommodate the expansive forces generated during ice formation.

The fly ash-containing mixtures showed progressively improving resistance to freeze-thaw-induced weight loss with increasing fly ash content. The weight loss values were 0.878%, 0.669%, and 0.24% for mixtures with 10%, 20%, and 30%

fly ash, respectively. The significant improvement at 30% fly ash content suggests that higher fly ash content contributes to enhanced freeze-thaw resistance, likely through pozzolanic reactions and pore refinement.
The granulated quartz mixtures exhibited increasing weight loss with higher quartz content. The weight loss values were 0.3%, 0.495%, and 0.678% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. The superior performance of the 10% granulated quartz mixture suggests an optimal replacement level, beyond which the benefits diminish.
Overall, the weight loss results corroborate the findings from the flexural and compressive strength tests, highlighting the superior performance of moderate-content marble dust mixtures and high-content fly ash mixtures in mitigating freeze-thaw damage.

3.4 Water Permeability of LECA Concrete Mixes

Water permeability is a crucial durability parameter for concrete, as it directly influences the ingress of aggressive agents and, consequently, the susceptibility to various deterioration mechanisms. The results of the water permeability test, in terms of water penetration depth, are presented in Figure 10.

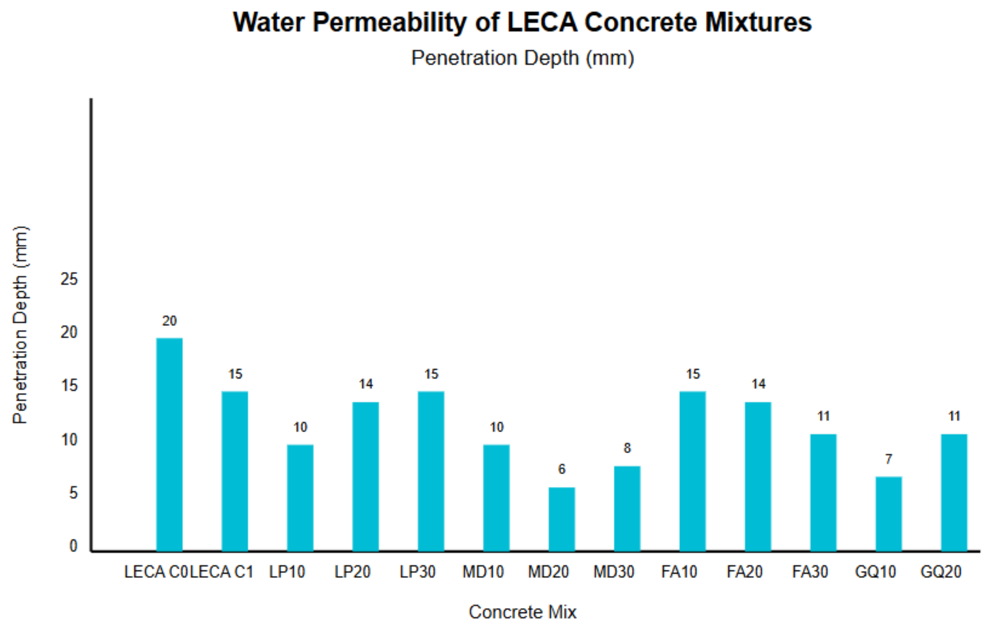

Figure 10: Water permeability of LECA concrete

The water permeability results, expressed in terms of water penetration depth, provide critical insights into the transport properties of LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited penetration depths of 20 mm and 15 mm, respectively. The reduction in penetration depth for LECA C1 compared to LECA C0 can be attributed to the pore refinement effect of silica fume, which improves the microstructure and reduces the permeability of the concrete.
The concrete mixtures containing lime powder demonstrated varying degrees of impermeability. The penetration depths were 10 mm, 14 mm, and 15 mm for mixtures with 10%, 20%, and 30% lime powder, respectively. These values correspond to reductions of 33.3%, 6.6%, and 0% compared to LECA C1. The superior performance of the 10% lime powder mixture suggests an optimal replacement level, beyond which additional lime powder becomes detrimental to impermeability.
The marble dust-containing mixtures exhibited exceptional resistance to water penetration, particularly at moderate replacement levels. The penetration depths were 10 mm, 6 mm, and 8 mm for mixtures with 10%, 20%, and 30% marble dust, respectively. These values correspond to reductions of 33.3%, 60%, and 46.6% compared to LECA C1. The remarkable performance of the 20% marble dust mixture, with a penetration depth of only 6 mm, indicates its effectiveness in reducing water permeability. This enhanced impermeability can be attributed to the filler effect of marble dust, which refines the pore structure and reduces the connectivity of the pore network.
The fly ash-containing mixtures showed progressively improving resistance to water penetration with increasing fly ash content. The penetration depths were 15 mm, 14 mm, and 11 mm for mixtures with 10%, 20%, and 30% fly ash, respectively. These values correspond to reductions of 0%, 6.6%, and 26.6% compared to LECA C1. The significant improvement at 30% fly ash content suggests that higher fly ash content contributes to enhanced impermeability, likely through pozzolanic reactions and pore refinement.

The granulated quartz mixtures exhibited varying resistance to water penetration. The penetration depths were 7 mm, 11 mm, and 14 mm for mixtures with 10%, 20%, and 30% granulated quartz, respectively. These values correspond to reductions of 53.3%, 26.6%, and 6.6% compared to LECA C1. The superior performance of the 10% granulated quartz mixture suggests an optimal replacement level, beyond which the benefits diminish.

Overall, the water permeability results highlight the superior performance of the 20% marble dust mixture and the 10% granulated quartz mixture in reducing water permeability. These findings are consistent with the results of the salt attack and freeze-thaw resistance tests, indicating a strong correlation between impermeability and resistance to various deterioration mechanisms.

3.5 Water Absorption of LECA Concrete Mixes

Water absorption is another important durability parameter that influences the susceptibility of concrete to various deterioration mechanisms. The results of the water absorption test, in terms of corrected absorption percentage after 30 minutes of immersion, are presented in Figure 11.

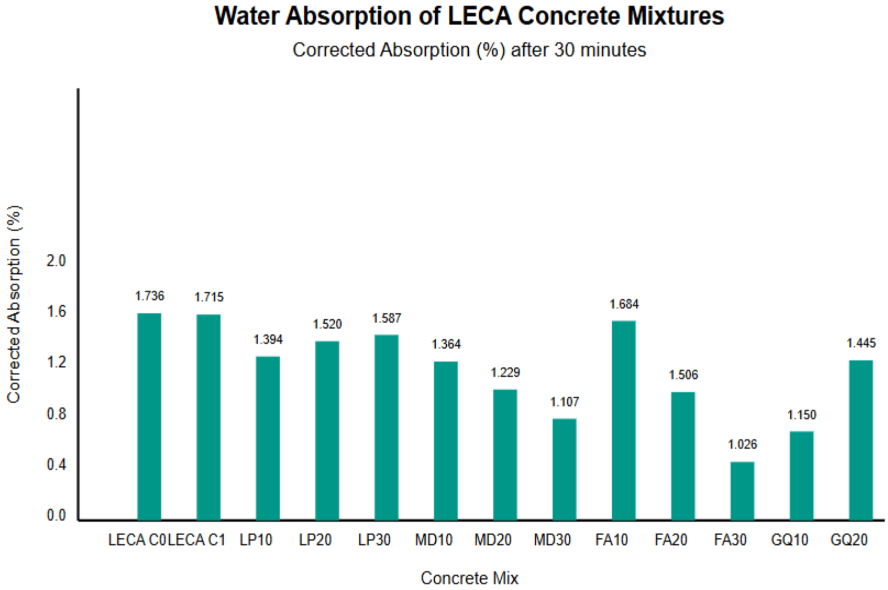

Figure 11: Water absorption of LECA concrete mixtures after 30 minutes

The water absorption results, expressed in terms of corrected absorption percentage after 30 minutes of immersion, provide valuable insights into the transport properties of LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited absorption values of 1.736% and 1.715%, respectively. The minimal reduction in absorption for LECA C1 compared to LECA C0 suggests that silica fume alone has a limited effect on the short-term water absorption of LECA concrete.

The concrete mixtures containing lime powder demonstrated varying degrees of resistance to water absorption. The absorption values were 1.394%, 1.520%, and 1.587% for mixtures with 10%, 20%, and 30% lime powder, respectively. These values correspond to reductions of 18.7%, 11.36%, and 7.47% compared to LECA C1. The increasing absorption with higher lime powder content suggests an optimal replacement level, beyond which additional lime powder becomes detrimental to water resistance.

The marble dust-containing mixtures exhibited exceptional resistance to water absorption, with a progressive reduction in absorption with increasing marble dust content. The absorption values were 1.364%, 1.229%, and 1.107% for mixtures with 10%, 20%, and 30% marble dust, respectively. These values correspond to reductions of 20.48%, 28.35%, and 35.47% compared to LECA C1. This significant improvement can be attributed to the filler effect of marble dust, which refines the pore structure and reduces the capillary porosity of the concrete.

The fly ash-containing mixtures showed progressively improving resistance to water absorption with increasing fly ash content. The absorption values were 1.684%, 1.506%, and 1.026% for mixtures with 10%, 20%, and 30% fly ash, respectively. These values correspond to reductions of 1.8%, 12.18%, and 40.17% compared to LECA C1. The remarkable improvement at 30% fly ash content suggests that higher fly ash content contributes to enhanced water resistance, likely through pozzolanic reactions and pore refinement.

The granulated quartz mixtures exhibited varying resistance to water absorption. The absorption values were 1.150%, 1.445%, and 1.563% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. These values correspond to reductions of 32.94%, 15.7%, and 8.85% compared to LECA C1. The superior performance of the 10% granulated quartz mixture suggests an optimal replacement level, beyond which the benefits diminish.

The corrected absorption rate over time (30, 60, 90, and 120 minutes) for all LECA concrete mixtures is presented in Figure 12.

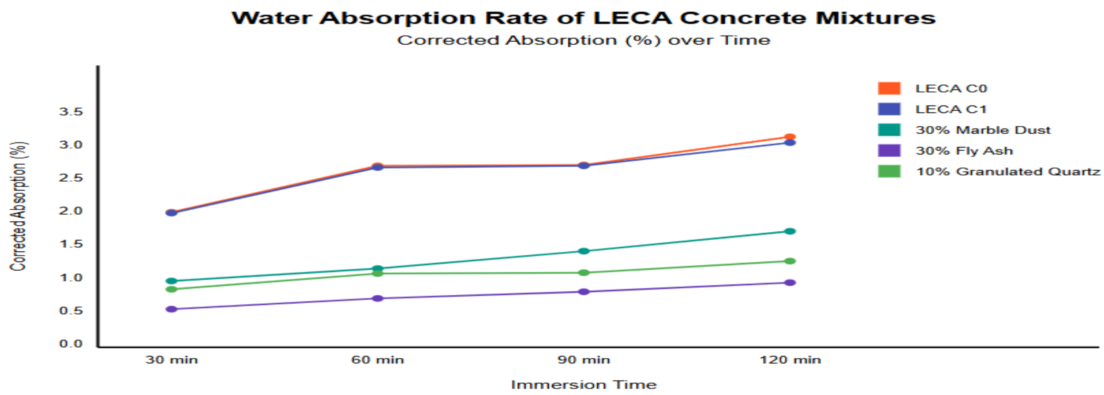

Figure 12: Water absorption rate of LECA concrete mixtures over time

The water absorption rate results provide insights into the time-dependent water absorption behavior of LECA concrete mixtures. The control mixtures (LECA C0 and LECA C1) exhibited rapid water absorption, with the rate increasing significantly within the first 60 minutes and then exhibiting a more gradual increase thereafter. After 120 minutes of immersion, the absorption values reached 3.059% and 2.918% for LECA C0 and LECA C1, respectively.
The concrete mixtures containing high percentages of mineral additives demonstrated significantly reduced water absorption rates compared to the control mixtures. The 30% marble dust mixture exhibited a remarkably low absorption rate, with values of 1.107%, 1.612%, 1.732%, and 2.093% after 30, 60, 90, and 120 minutes of immersion, respectively. These values correspond to reductions of 35.47%, 37.03%, 33.01%, and 28.27% compared to LECA C1. The relatively flat slope of the absorption curve indicates a significant reduction in the capillary suction forces, which can be attributed to the refined pore structure and reduced pore connectivity. The 30% fly ash mixture demonstrated the lowest overall absorption rate, with values of 1.026%, 1.368%, 1.515%, and 1.783% after 30, 60, 90, and 120 minutes of immersion, respectively. These values correspond to reductions of 40.18%, 46.56%, 41.42%, and 38.89% compared to LECA C1. This exceptional performance can be attributed to the pozzolanic reaction of fly ash, which consumes calcium hydroxide and forms additional C-S-H, resulting in a refined pore structure with reduced capillary porosity.
The 10% granulated quartz mixture also exhibited a reduced absorption rate, with values of 1.150%, 1.584%, 1.610%, and 1.916% after 30, 60, 90, and 120 minutes of immersion, respectively. These values correspond to reductions of 32.97%, 38.12%, 37.74%, and 34.34% compared to LECA C1. The improved performance can be attributed to the filler effect of granulated quartz, which refines the pore structure and reduces the capillary porosity.
Overall, the water absorption rate results highlight the superior performance of high-content fly ash mixtures, followed by moderate-content marble dust mixtures and low-content granulated quartz mixtures, in reducing water absorption. These findings are consistent with the results of the water permeability test and further emphasize the importance of optimizing the mineral additive type and content for specific durability requirements.
3.6 Chloride and Sulfate Content of LECA Concrete Mixes
The chloride and sulfate content of hardened concrete is a critical parameter that influences the susceptibility to reinforcement corrosion and chemical attack. The results of the chloride and sulfate content tests for all LECA concrete mixtures are presented in Figures 13 and 14, respectively.

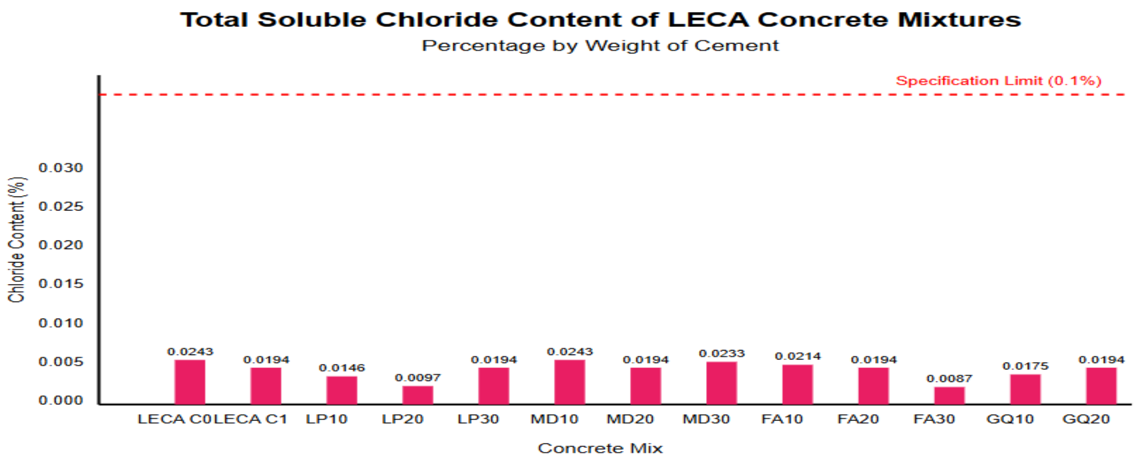

Figure 13: Chloride content of LECA concrete mixtures

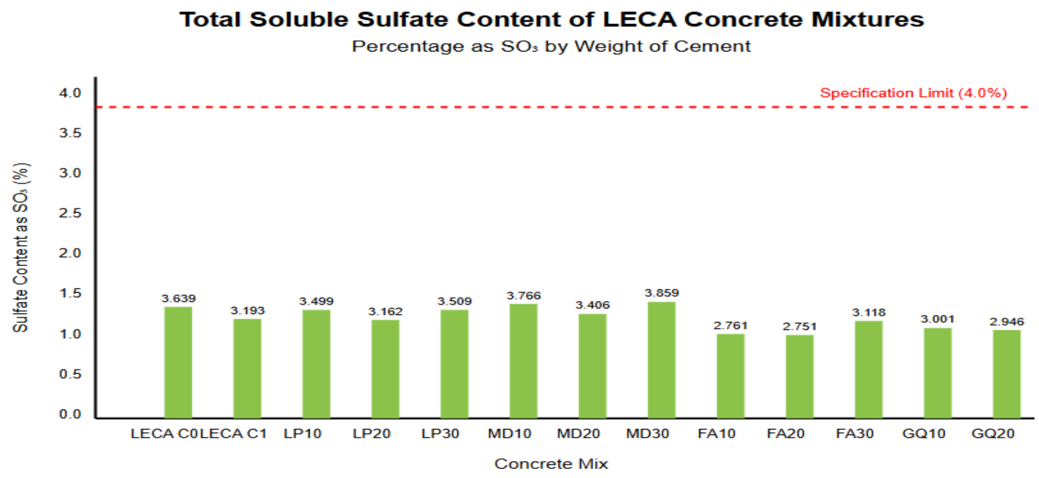

Figure 14: Sulfate content of LECA concrete mixtures

The chloride content results reveal that all LECA concrete mixtures exhibited chloride contents well below the specification limit of 0.1% by weight of cement, as stipulated in ECP 203-2020. The control mixtures (LECA C0 and LECA C1) had chloride contents of 0.02428% and 0.01943%, respectively. The reduction in chloride content for LECA C1 compared to LECA C0 can be attributed to the dilution effect of silica fume, which partially replaces cement.

Among the lime powder-containing mixtures, the 10% and 20% replacement levels demonstrated reduced chloride contents of 0.01457% and 0.00971%, respectively, while the 30% replacement level exhibited a chloride content similar to LECA C1. The significant reduction achieved with the 20% lime powder mixture can be attributed to the dilution effect and potentially improved chloride binding capacity.

The marble dust-containing mixtures showed varying chloride contents. The 10% replacement level exhibited a chloride content similar to LECA C0, while the 20% and 30% replacement levels exhibited chloride contents of 0.01943% and 0.02331%, respectively. These results suggest that marble dust has a limited influence on the chloride content of LECA concrete.

The fly ash-containing mixtures demonstrated progressively decreasing chloride contents with increasing fly ash content. The chloride contents were 0.02137%, 0.01943%, and 0.00874% for mixtures with 10%, 20%, and 30% fly ash, respectively. The remarkable reduction achieved with the 30% fly ash mixture can be attributed to the combined effect of dilution and enhanced chloride binding capacity due to the increased aluminate content from fly ash.

The granulated quartz mixtures exhibited varying chloride contents. The 10% replacement level demonstrated a reduced chloride content of 0.01748%, while the 20% and 30% replacement levels exhibited chloride contents of 0.01943% each. These results suggest that granulated quartz has a moderate influence on the chloride content of LECA concrete.

The sulfate content results indicate that all LECA concrete mixtures exhibited sulfate contents (expressed as SO_3) well below the specification limit of 4.0% by weight of cement, as stipulated in ECP 203-2020. The control mixtures (LECA C0 and LECA C1) had sulfate contents of 3.639% and 3.193%, respectively. The reduction in sulfate content for LECA C1 compared to LECA C0 can be attributed to the dilution effect of silica fume.

Among the mineral additives investigated, the fly ash-containing mixtures exhibited the lowest sulfate contents, with values of 2.761%, 2.751%, and 3.118% for mixtures with 10%, 20%, and 30% fly ash, respectively. This reduction can be attributed to the dilution effect and potentially to the sulfate binding capacity of fly ash due to its aluminate content.

The granulated quartz mixtures also demonstrated reduced sulfate contents, with values of 3.001%, 2.946%, and 3.029% for mixtures with 10%, 20%, and 30% granulated quartz, respectively. This reduction can be attributed primarily to the dilution effect of granulated quartz.

The lime powder and marble dust mixtures exhibited sulfate contents comparable to or slightly higher than LECA C1, suggesting limited influence on the sulfate content of LECA concrete. However, it is important to note that all mixtures remained well below the specification limit, indicating acceptable sulfate levels for construction applications.

4. Discussion

The comprehensive durability assessment of LECA-based self-compacted lightweight concrete with various mineral additives has revealed several significant findings with important implications for practical applications. This section discusses the key observations and their underlying mechanisms, focusing on the relationships between different durability parameters and the optimal mineral additive types and proportions for specific environmental conditions.

4.1 Influence of Mineral Additives on Resistance to Salt Attack

The resistance to salt attack, both sulfate and chloride, demonstrated clear dependencies on the type and proportion of mineral additives. Marble dust at 20% replacement exhibited the best performance against sulfate attack, with only 12.21% reduction in flexural strength compared to the control mixture's 17.62% reduction. This superior performance can be attributed to several mechanisms:

1. Pore Refinement: Marble dust particles, being finer than cement, fill the interstitial spaces between cement particles, leading to a denser microstructure with reduced pore connectivity. This physical effect restricts the penetration of sulfate ions into the concrete matrix.

2. Dilution of Reactive Components: Marble dust, being primarily calcium carbonate, partially replaces cement and thus reduces the content of tricalcium aluminate (C_3A), which is the primary reactant in sulfate attack. This dilution effect reduces the formation of expansive reaction products such as ettringite.

3. Enhanced Nucleation Sites: The fine marble dust particles provide additional nucleation sites for the precipitation of calcium silicate hydrate (C-S-H), resulting in a more homogeneous microstructure with improved resistance to sulfate-induced expansion.

Similarly, for chloride attack, granulated quartz at 10% replacement demonstrated the best performance, with only 14.79% reduction in flexural strength compared to the control mixture's 29.5% reduction. This enhanced resistance can be attributed to:

1. Refined Pore Structure: The fine granulated quartz particles improve the particle packing density, reducing the pore size and connectivity, which restricts the ingress of chloride ions.

2. Enhanced C-S-H Formation: The silica content in granulated quartz participates in pozzolanic reactions, consuming calcium hydroxide and forming additional C-S-H, which reduces the permeability of the concrete matrix.

3. Reduced Capillary Pores: The incorporation of granulated quartz reduces the water-to-cement ratio required for workability, leading to reduced capillary porosity and enhanced resistance to chloride penetration.

Fly ash also demonstrated progressively improving resistance to both sulfate and chloride attacks with increasing replacement levels, with the 30% replacement exhibiting remarkable performance. This trend can be explained by:

1. Pozzolanic Reaction: Fly ash reacts with calcium hydroxide produced during cement hydration to form additional C-S-H, resulting in a denser microstructure with reduced permeability.

2. Aluminate Binding: The aluminate content in fly ash can bind with chloride ions to form insoluble Friedel's salt, reducing the free chloride concentration that can cause reinforcement corrosion.

3. Reduced Permeability: The fine spherical particles of fly ash improve the particle packing density and reduce the water demand, resulting in reduced permeability and enhanced resistance to salt ingress.

4.2 Influence of Mineral Additives on Freeze-Thaw Resistance

The freeze-thaw resistance demonstrated strong correlations with the pore structure characteristics influenced by different mineral additives. Marble dust at 20% replacement exhibited the best performance, with only 5.91% reduction in compressive strength compared to the control mixture's 17.1% reduction. This enhanced resistance can be attributed to:

1. Reduced Freezable Water Content: The refined pore structure resulting from marble dust incorporation reduces the amount of freezable water within the concrete matrix, limiting the expansion forces during freezing.

2. Improved Pore Size Distribution: Marble dust alters the pore size distribution, potentially creating a more uniform network of smaller pores that can better accommodate ice expansion.

3. Enhanced Microstructural Integrity: The improved particle packing density from marble dust incorporation enhances the overall integrity of the microstructure, allowing it to better withstand the stresses induced by freeze-thaw cycles.

Fly ash at 30% replacement also demonstrated excellent freeze-thaw resistance, with only 8.09% reduction in compressive strength. This can be attributed to similar mechanisms of pore refinement and reduced permeability, as well as the potential for increased air entrainment, which provides expansion chambers for ice formation.

4.3 Influence of Mineral Additives on Water Transport Properties

The water transport properties, including permeability and absorption, exhibited significant improvements with specific mineral additives. Marble dust at 20% replacement demonstrated a remarkable 60% reduction in water penetration depth compared to the control mixture. Similarly, fly ash at 30% replacement exhibited a 40.18% reduction in water absorption after 30 minutes of immersion.

These improvements in water transport properties can be linked to the microstructural modifications induced by these mineral additives:

1. Reduced Pore Connectivity: The incorporation of fine particles fills the interstitial spaces between cement particles, reducing the connectivity of the pore network and limiting water transport pathways.

2. Refined Pore Size Distribution: The mineral additives alter the pore size distribution, reducing the volume of larger capillary pores responsible for rapid water ingress.

3. Enhanced Hydration Products: Pozzolanic additives like fly ash form additional C-S-H, which fills the pore spaces and reduces the overall porosity of the concrete matrix.

The strong correlation between water transport properties and resistance to salt attack and freeze-thaw damage underscores the importance of impermeability in enhancing overall durability. The reduced ingress of aggressive agents limits their potential for causing deterioration, while the reduced water content minimizes the freeze-thaw damage potential.

4.4 Optimal Mineral Additive Types and Proportions

Based on the comprehensive durability assessment, the following recommendations can be made regarding the optimal mineral additive types and proportions for specific environmental conditions:

1. For Sulfate-Rich Environments: Marble dust at 20% replacement offers the best resistance to sulfate attack, with minimal deterioration in flexural and compressive strengths. Fly ash at 30% replacement also demonstrates excellent sulfate resistance and would be suitable for sulfate-rich environments.

2. For Chloride-Rich Environments: Granulated quartz at 10% replacement provides superior resistance to chloride attack, making it ideal for marine environments or structures exposed to deicing salts. Fly ash at 30% replacement is also highly effective in mitigating chloride-induced deterioration.

3. For Freeze-Thaw Environments: Marble dust at 20% replacement offers the best freeze-thaw resistance, with minimal deterioration in mechanical properties after exposure to freeze-thaw cycles. This makes it suitable for cold regions with frequent freeze-thaw cycles.

4. For Impermeable Concrete: Marble dust at 20% replacement and fly ash at 30% replacement offer exceptional impermeability, making them suitable for water-retaining structures or structures requiring high impermeability.

5. For Overall Durability: A combination of 10% silica fume with 20% marble dust offers a balanced improvement in all durability parameters, making it suitable for a wide range of environmental conditions. Alternatively, a combination of 10% silica fume with 30% fly ash also offers excellent overall durability.

It is important to note that the optimal mineral additive type and proportion may vary depending on the specific requirements and environmental conditions. The recommendations provided above are based on the findings of this study and may need to be adjusted based on additional factors such as cost, availability, and specific project requirements.

5. Conclusions

Based on the comprehensive durability assessment of LECA-based self-compacted lightweight concrete with various mineral additives, the following conclusions can be drawn; The incorporation of mineral additives significantly enhances the durability characteristics of LECA-based self-compacted lightweight concrete, with the extent of improvement depending on the type and proportion of the mineral additive. Marble dust at 20% replacement demonstrates superior resistance to sulfate attack, with only 12.21% reduction in flexural strength compared to the control mixture's 17.62% reduction, making it suitable for concrete structures in sulfate-rich environments. Granulated quartz at 10% replacement exhibits exceptional resistance to chloride attack, with only 14.79% reduction in flexural strength compared to the control mixture's 29.5% reduction, making it ideal for marine environments or structures exposed to deicing salts. Marble dust at 20% replacement offers the best freeze-thaw resistance, with only 5.91% reduction in compressive strength compared to the control mixture's 17.1% reduction, making it suitable for cold regions with frequent freeze-thaw cycles. Marble dust at 20% replacement demonstrates a remarkable 60% reduction in water penetration depth, while fly ash at 30% replacement exhibits a 40.18% reduction in water absorption, highlighting their effectiveness in enhancing the impermeability of LECA concrete. All LECA concrete mixtures with mineral additives maintain chloride and sulfate contents well below the specification limits, indicating their suitability for construction applications. The enhanced durability characteristics of mineral additive-incorporated LECA concrete can be attributed to pore refinement, reduced permeability, pozzolanic reactions, and improved microstructural integrity, depending on the specific mineral additive. The optimal mineral additive type and proportion for a specific application should be selected based on the environmental conditions, durability requirements, and other project-specific factors.

These findings provide valuable insights for engineers and researchers seeking to develop durable lightweight concrete formulations for challenging environmental conditions. The strategic incorporation of mineral additives, particularly marble dust and fly ash, offers a promising approach to enhancing the durability of LECA-based self-compacted lightweight concrete, potentially extending the service life of concrete structures and reducing maintenance costs.

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