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# Mechanical Behavior of Internally-Cured LECA Mortar in Acidic Marine Conditions

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## ABSTRACT

Cementitious materials used in coastal and offshore infrastructures are frequently subjected to aggressive acidic environments resulting from industrial discharge, marine pollution, and sulfur-based biochemical processes. This study examines the mechanical behavior and acid resistance of mortar incorporating lightweight expanded clay aggregate (LECA) as an environmentally sustainable partial replacement for natural sand, with the added benefit of internal curing. Four mortar mixtures containing 0%, 5%, 10%, and 15% LECA were prepared, water-cured for 28 days, and subsequently exposed to a sulfuric acid solution (pH 1.5) for up to 90 days to simulate severe acid attack. Compressive strength, flexural strength, mass loss, and strength–degradation correlations were evaluated. Results indicate that LECA replacement does not compromise initial mechanical performance, while the mixture containing 10% LECA exhibited the highest long-term durability under acid exposure, demonstrating reduced mass loss and significantly lower strength degradation compared to the control mix. The enhanced performance is attributed to the internal curing effect of LECA and its ability to mitigate microcracking in chemically aggressive environments. These findings highlight the potential of LECA-modified mortar as a sustainable and durable alternative for coastal and offshore structures subjected to acidic conditions.

## 1. Introduction

In recent years, environmental protection and sustainability have become major global concerns [1]. Among the various environmental challenges, air pollution has contributed to the formation of acid rain, which has been widely reported in coastal and industrial regions of the United States, Europe, and Asia [2]. Acidic precipitation poses a serious threat to concrete infrastructure, particularly in marine and coastal environments, where exposure conditions are often more aggressive, leading to accelerated material degradation and substantial economic losses associated with repair and rehabilitation [3]. Acid rain may contain aggressive chemical compounds such as sulfuric and nitric acids, which intensify the chemical attack on cement-based materials [4].

Acidic exposure is one of the most critical durability-related factors affecting concrete structures in coastal, offshore, and port facilities [5]. This issue is especially pronounced in marine storage tanks, harbor infrastructures, and offshore industrial units where sulfuric acid and other corrosive substances are commonly present, as illustrated in Figure 1 [6,7]. Under such conditions, concrete elements are simultaneously subjected to mechanical loading and severe chemical attack, making both strength retention and long-term durability essential performance requirements [8]. Therefore, evaluating the mechanical behavior of concrete exposed to acidic marine environments is of paramount importance for predicting service life and ensuring the structural reliability of coastal and offshore concrete infrastructure.

**Figure 1. Reinforced concrete sulfuric acid storage tanks located at Bandar Abbas Port, Iran.**

Acid-induced deterioration of concrete represents a challenging research topic that has been widely examined by various researchers. Sharifi et al. evaluated the durability performance of self-compacting concrete subjected to acidic environments and reported that sulfuric acid induced significantly greater damage than hydrochloric acid. [9]. Similarly, Irico et al. examined self-compacting concrete incorporating fly ash under sulfuric acid exposure. Scanning electron microscopy observations indicated that fly ash enhanced resistance to acid attack, highlighting its potential role in improving the acid durability of concrete [10]. Furthermore, Sharifi and Ranjbar investigated mortar mixtures containing ceramic powder waste exposed to acidic conditions. Their findings demonstrated that prolonged acid exposure resulted in increased mass loss and substantial reductions in the mechanical strength of the mortar specimens [11].

Another environmental challenge is the excessive extraction of river sand, which threatens the ecosystems of river channels and floodplains. Consequently, researchers are increasingly seeking sustainable alternatives to natural river sand in the construction industry. Lightweight expanded clay aggregate (LECA) is a promising substitute, as it not only reduces the overall weight of the mixture but also provides internal curing, helping retain moisture and mitigate cracking in concrete. LECA can serve as a suitable replacement for natural sand, as it not only reduces the overall weight of the mixture but also provides internal curing, helping to retain moisture within the concrete and prevent cracking in various environmental conditions [12-14].

The objective of this study is to determine the optimal replacement level of LECA, incorporating internal curing, as a substitute for natural sand in structural mortar, in order to achieve maximum compressive and flexural strength under acidic exposure conditions representative of coastal and marine environments. To this end, four mortar mixtures were prepared in which 0%, 5%, 10%, and 15% of sand was replaced with LECA. Cubic and prismatic mortar specimens were cast and water-cured for 28 days. Subsequently, to simulate aggressive acidic conditions commonly encountered in marine and port infrastructures, the specimens were exposed to a sulfuric acid solution with a pH of 1.5 for periods of 0, 3, 7, 14, 28, 56, and 90 days. The mechanical performance and mass loss behavior of the mortar specimens were systematically investigated, and the corresponding results are discussed.

## 2. Materials

The fine aggregate used in this study was crushed mountain sand sourced from the Arak region, Iran. The physical properties of the sand complied with the requirements of ASTM C33 [15]. The cement used was Type II Portland cement produced by the Nahavand Cement Plant, located in western Iran, with chemical and physical properties conforming to ASTM C150 [16]. Potable water of acceptable quality was used for mixing and curing purposes; the water was clean and free from harmful impurities such as iron oxides, acids, alkalis, salts, organic matter, and chloride ions.

### 2.1. LECA

LECA is produced from natural clay with a small amount of lime. The clay is first dried and then heated in rotary kilns at temperatures typically ranging from 1100 to 1300 °C. During the heating process, gases are released within the clay particles and become trapped upon cooling, resulting in the formation of spherical aggregates with a highly porous internal structure, as illustrated in Figure 2. These aggregates are lightweight yet exhibit high resistance to crushing [12]. LECA is chemically stable and does not react with water; therefore, it is not adversely affected by prolonged water exposure. The chemical composition of LECA primarily consists of silica ($SiO_2$), alumina ($Al_2O_3$), iron oxide ($Fe_2O_3$), lime (CaO), and minor amounts of alkali oxides such as sodium oxide ($Na_2O$) and potassium oxide ($K_2O$) [17,18].

**Figure 2. Physical appearance of LECA utilized as internal curing aggregate in this study.**

### 2.2. Sulfuric Acid

Acid rain typically contains a significant amount of sulfuric acid [19]. In this study, to simulate such an environment, the specimens were exposed to a sulfuric acid solution with a pH level of 1.5 [11,20]. The pH value was regularly monitored using a digital pH meter, and the acidic solution was maintained at a constant pH throughout the experiment.

## 3. Internal Curing

In certain concrete mixtures, particularly those with a low water-to-cement ratio, internal drying poses a significant risk due to insufficient available water, which may prevent complete cement hydration and consequently reduce concrete performance. Since most conventional curing practices are applied to the concrete surface, their effectiveness is largely confined to a shallow region near the surface. As a result, external curing methods may have limited influence on mixtures that are highly susceptible to internal drying [21]. An innovative approach to address this challenge is the provision of internal curing, in which additional water required for cement hydration is supplied from within the concrete matrix. This internal water is not part of the initial mixing water and therefore does not alter the original water-to-cement ratio. The use of water-absorbing aggregates capable of storing and gradually releasing moisture over time is an effective strategy to achieve this objective [22].

Various internal curing methods have been classified based on the recommendations of the RILEM Technical Committee ICC–196TC. In general, internal curing refers to the incorporation of a component into concrete that acts as an internal curing agent. This component may consist of an aggregate introduced under specific conditions, such as a pre-saturated state, or a specialized admixture [23,24]. However, the definition of internal curing provided by the American Concrete Institute (ACI) differs slightly from that of RILEM. According to ACI, internal curing is defined as a process by which cement hydration progresses due to the availability of additional internal water that is not part of the original mixing water [25].

In this study, LECA was employed to provide internal curing. Prior to incorporation into the mixture, LECA particles were pre-soaked in water for 24 hours to absorb the amount of water required for internal curing. Subsequently, the aggregates were added to the mix in a saturated surface-dry condition. The absorbed water within the LECA is gradually released over several days, facilitating continued cement hydration and potentially eliminating the need for external curing. Therefore, the internal water stored in saturated surface-dry LECA satisfies the internal curing criteria as defined by the American Concrete Institute.

## 4. Mix Design

As previously mentioned, this study investigates the effect of incorporating different percentages of LECA under internal curing conditions on the mechanical properties of structural mortar in an acidic environment. Accordingly, cubic specimens with dimensions of 50 × 50 × 50 mm were prepared to evaluate compressive strength, while prismatic specimens with dimensions of 160 × 40 × 40 mm were fabricated to assess flexural strength. In this research, the influence of replacing sand with LECA at levels of 0%, 5%, 10%, and 15% in structural mortar exposed to an acidic environment was examined, as listed in **Error! Reference source not found.**.

Specimen casting and preparation were carried out in accordance with ASTM C192 [26]. After casting, the molds were sealed in plastic bags for 24 hours to prevent moisture loss due to ambient temperature. Following this period, the specimens were demolded and cured in a water tank for 28 days. Subsequently, based on the designated exposure durations, the specimens were transferred to acid-resistant polyethylene tanks containing sulfuric acid solution. It should be noted that the pH of the sulfuric acid bath was maintained at 1.5, a value selected based on previous studies and estimations of the long-term deteriorating effects of acid rain and industrial wastewater leachates on concrete [11,20].

**Table 1: Mix Design**

| No. | Mix Design Name | W/C | LECA (٪) | Materials Used in the Mixed Design for One Cubic meter (kg/$m^3$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | **LECA** | **Cement** | **Water** | **Fine Aggregate (Sand)** |
| 1 | ML0 | 0.45 | 0 | 0 | 670 | 301 | 1177 |
| 2 | ML5 | 0.45 | 5 | 37 | 670 | 301 | 1118 |
| 3 | ML10 | 0.45 | 10 | 73 | 670 | 301 | 1059 |
| 4 | ML15 | 0.45 | 15 | 110 | 670 | 301 | 1001 |

# 5. results and Discussion

## 5.1. Compressive Strength Test Results

The results of the compressive strength tests conducted on cubic mortar specimens with dimensions of 50 × 50 × 50 mm are discussed for different exposure periods following 28 days of standard water curing and subsequent immersion in an acidic environment. For each testing age, the average compressive strength was calculated as the mean value of three specimens. The obtained results are evaluated and presented in Figures 2 and 3.

According to the compressive strength results presented in Figure 2, all specimens exhibited nearly identical strength values prior to acid exposure, with only minor differences observed. This indicates that the incorporation of LECA under internal curing conditions did not adversely affect the initial compressive strength of the mortar. As expected, acidic exposure led to progressive deterioration and a reduction in compressive strength over time. All specimens experienced strength loss under acid attack, reaching their minimum compressive strength after 90 days of exposure.

After 3 days of acid exposure, specimen ML10 exhibited higher compressive strength than the other mixtures, indicating that the incorporation of 10% LECA was beneficial at this early stage of acidic exposure. In contrast, specimen ML15 showed the lowest compressive strength at all ages, except at 90 days. After 7 days of exposure, specimen ML0 demonstrated the highest compressive strength, while at 14 days both ML0 and ML10 exhibited superior compressive strength compared to the other mixtures. After 28 days of acid exposure, the compressive strengths of all specimens became very close, with only minor differences observed, and were approximately 30% of their initial strength values. Nevertheless, specimen ML10 exhibited slightly higher compressive strength compared to the other mixtures. At 56 days, the mixture containing 10% LECA continued to demonstrate superior resistance performance. After 90 days of exposure, specimen ML0 showed the lowest compressive strength, while specimens incorporating 5%, 10%, and 15% LECA exhibited relatively similar strength levels but consistently higher values than the control mixture. These results indicate that the presence of LECA contributes to improved long-term compressive strength performance of cement mortar under acidic conditions.

The compressive strength reduction (CSR)relative to the control specimen was calculated using Eq.(1), based on varying LECA content and exposure duration in the acidic environment. The results are illustrated in Figures 3, where *CS* represents the compressive strength of the specimen at a given LECA replacement level and exposure day, and $CS_c$ denotes the compressive strength of the control specimen.

$$\mathrm{CSR} = \frac{CS - CS_c}{CS_c} \times 100 \tag{1}$$

Figure 3 illustrates the CSR of the mortar specimens under acidic exposure. As observed, specimen ML10 exhibited a lower CSR after 3 days of exposure compared to the other mixtures. As expected, all specimens experienced strength loss under acid attack; however, the control specimen showed a greater CSR over longer exposure periods. Specifically, at 56 and 90 days, the control mixture exhibited the highest percentage of strength reduction, whereas specimen ML10 demonstrated the lowest CSR at these ages.

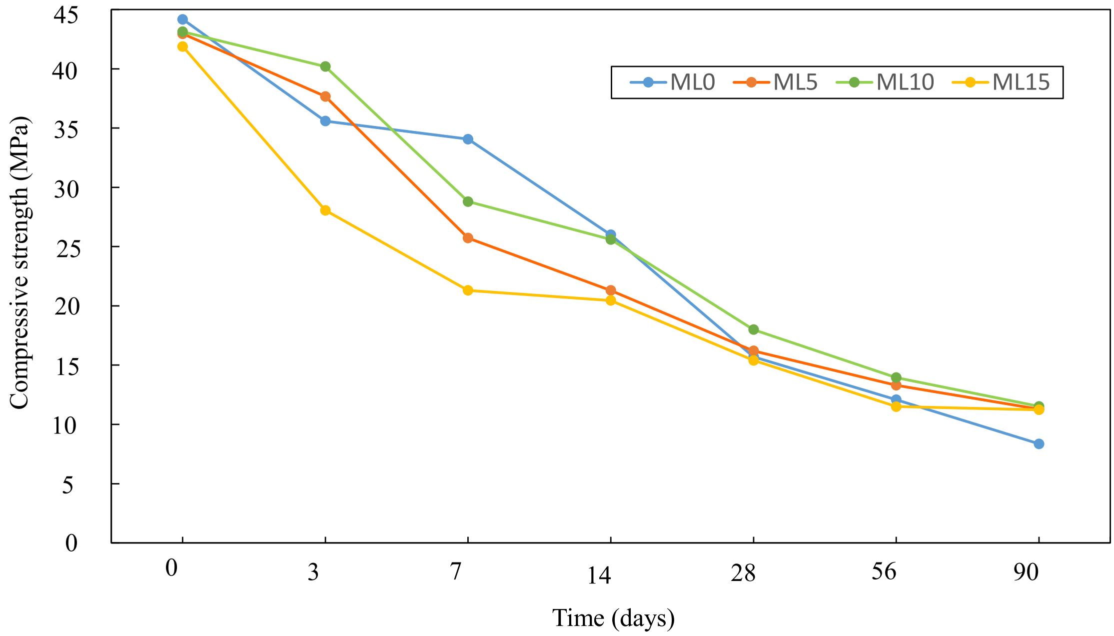

**Figure 2. Effect of LECA content and acidic exposure on the compressive strength of mortar.**

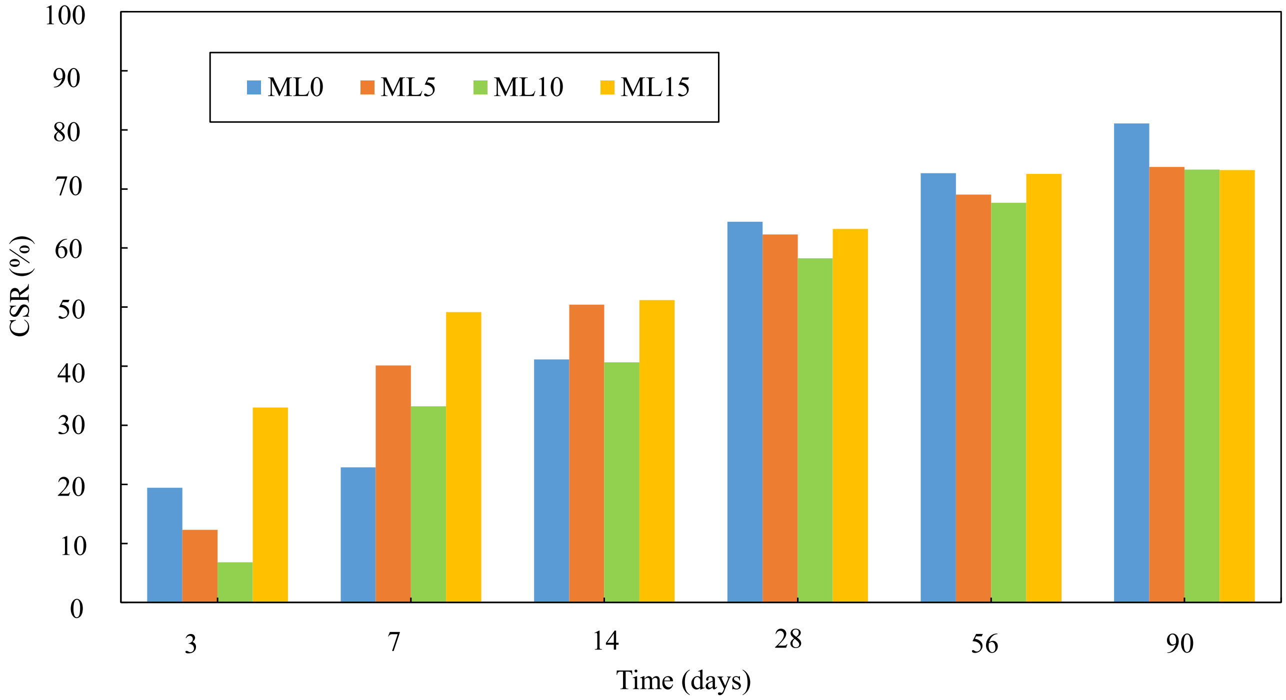

**Figure 3. CSR of mortar as a function of exposure time to sulfuric acid.**

## 5.2. Flexural Strength Test Results

The results of the flexural strength tests conducted on prismatic mortar specimens with dimensions of 160 × 40 × 40 mm are examined for different exposure periods following 28 days of standard water curing and subsequent immersion in an acidic environment. For each testing age, the average flexural strength was calculated as the mean value of three specimens. The corresponding results are presented in Figure 4.

Prior to acid exposure, specimen ML10 exhibited the highest flexural strength, while specimen ML5 showed a marginally lower value, with a difference of approximately 4.1%, which can be considered negligible. Accordingly, it can be inferred that incorporating 5% to 10% LECA in the mixture is suitable before exposure to acidic conditions. After 3 days of acid exposure, specimens ML0 and ML10 demonstrated higher flexural strength compared to the other mixtures. At subsequent ages, specimen ML10 consistently exhibited the highest flexural strength, indicating that the inclusion of 10% LECA is beneficial for cement mortar exposed to acidic environments. In contrast, specimen ML15 exhibited the lowest flexural strength at 7 days, while specimen ML0 showed the lowest value at 14 days.

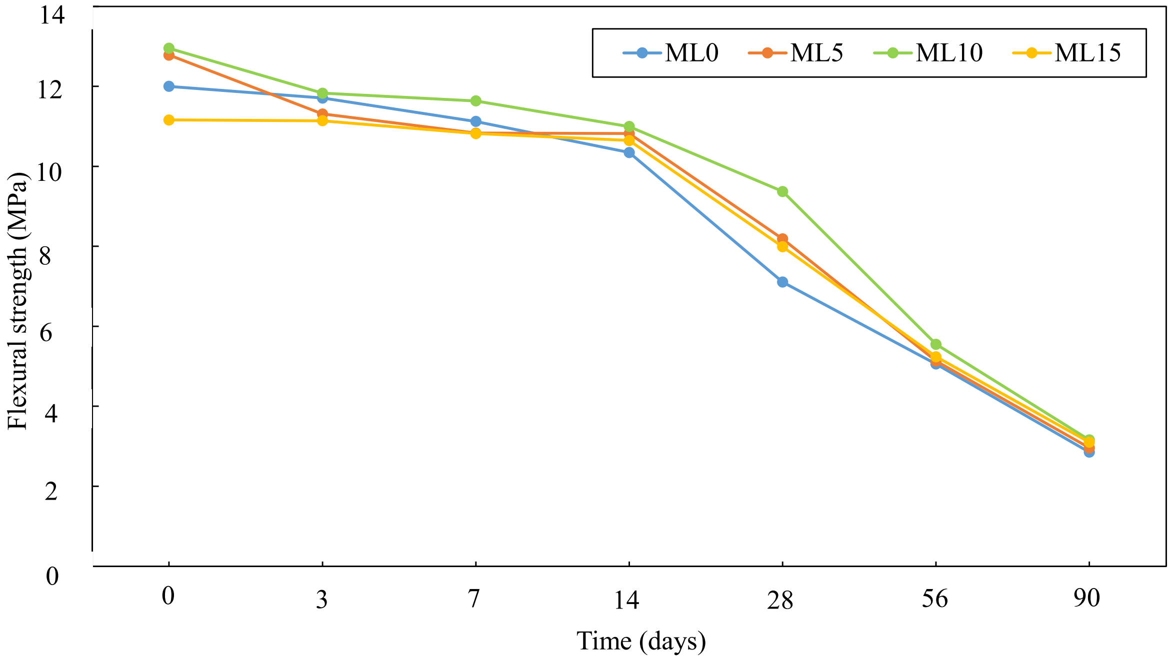

**Figure 4. Effect of LECA content and acidic exposure on the flexural strength of mortar.**

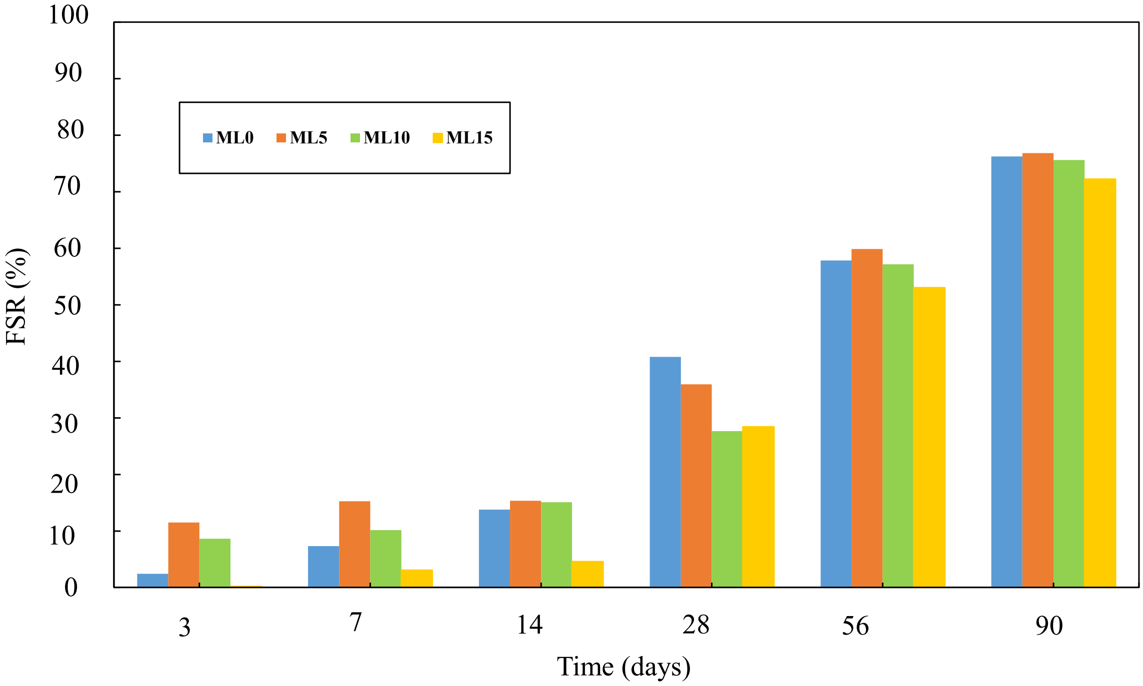

**Figure 4. Effect of LECA content and acidic exposure on the flexural strength of mortar.**

After 28 days of acid exposure, the reduction in flexural strength of specimens ML0, ML5, and ML15 occurred at a steeper rate compared to specimen ML10. At this age, the control mixture exhibited the lowest flexural strength, whereas specimen ML10 maintained the highest value with a noticeable margin. At 56 and 90 days, the flexural strengths of all specimens converged to similar levels, showing only minor differences; however, specimen ML10 continued to demonstrate relatively better resistance performance compared to the other mixtures.

The flexural strength reduction (FSR)relative to the control specimen was calculated using Eq.(2), based on varying LECA content and exposure duration in the acidic environment. The results are illustrated in Figures 5, where *FS* represents the flexural strength of the specimen at a given LECA replacement level and exposure day, and $FS_c$ denotes the flexural strength of the control specimen.

$$\text{FSR} = \frac{FS - FS_c}{FS_c} \times 100 \tag{2}$$

As shown in Figures 5, after 3 days of exposure, specimen ML15 exhibited a negligible FSR, and at subsequent ages its strength degradation progressed more gradually compared to the other mixtures. In addition, the flexural strength of specimens ML5 and ML10 decreased progressively at 3, 7, and 14 days. However, after 14 days of exposure, a pronounced FSR was observed for all specimens, with specimen ML0 exhibiting the highest FSR and specimen ML10 showing the lowest FSR at this age. Furthermore, it is evident that at 56 and 90 days, the FSR reached its maximum values for all mixtures.

### 5.3. Mass Loss

As shown in Figure 6, acidic exposure caused surface deterioration and degradation of the mortar specimens. With increasing exposure duration, the specimens experienced more severe damage, accompanied by a reduction in both volume and mass. The variation in mortar mass over the exposure period of 0 to 90 days is presented in Figure 7. At each testing age, the masses of the specimens were relatively close, and no significant differences were observed. Moreover, the mass loss trends of all mixtures followed a similar pattern.

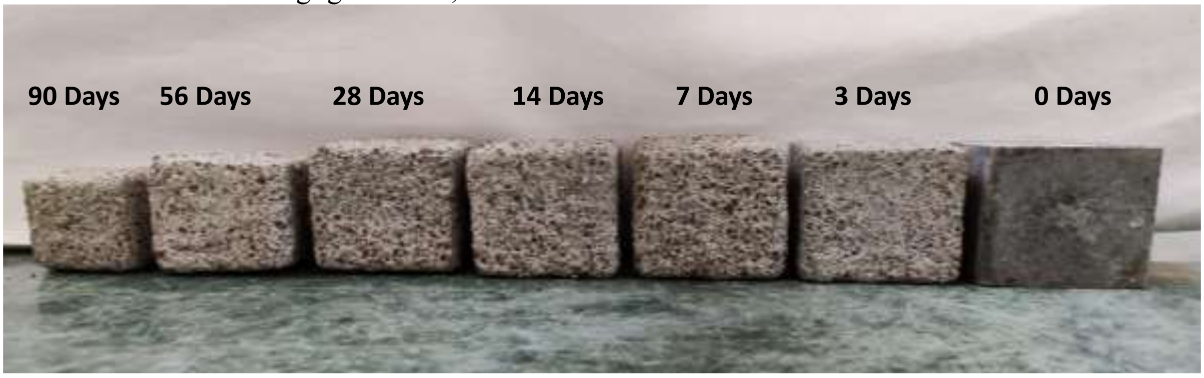

**Figure 6. Surface deterioration of a cubic mortar specimen resulting from sulfuric acid exposure.**

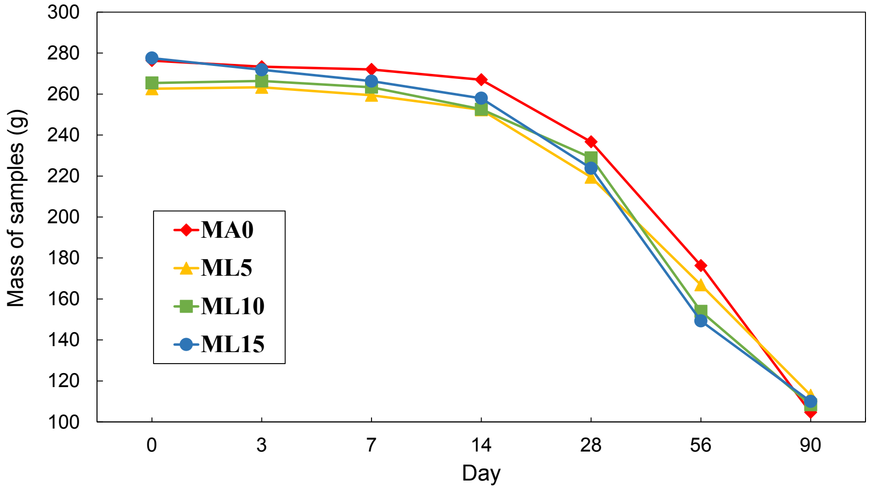

**Figure 7. Mass loss of cubic mortar specimens subjected to acidic exposure.**

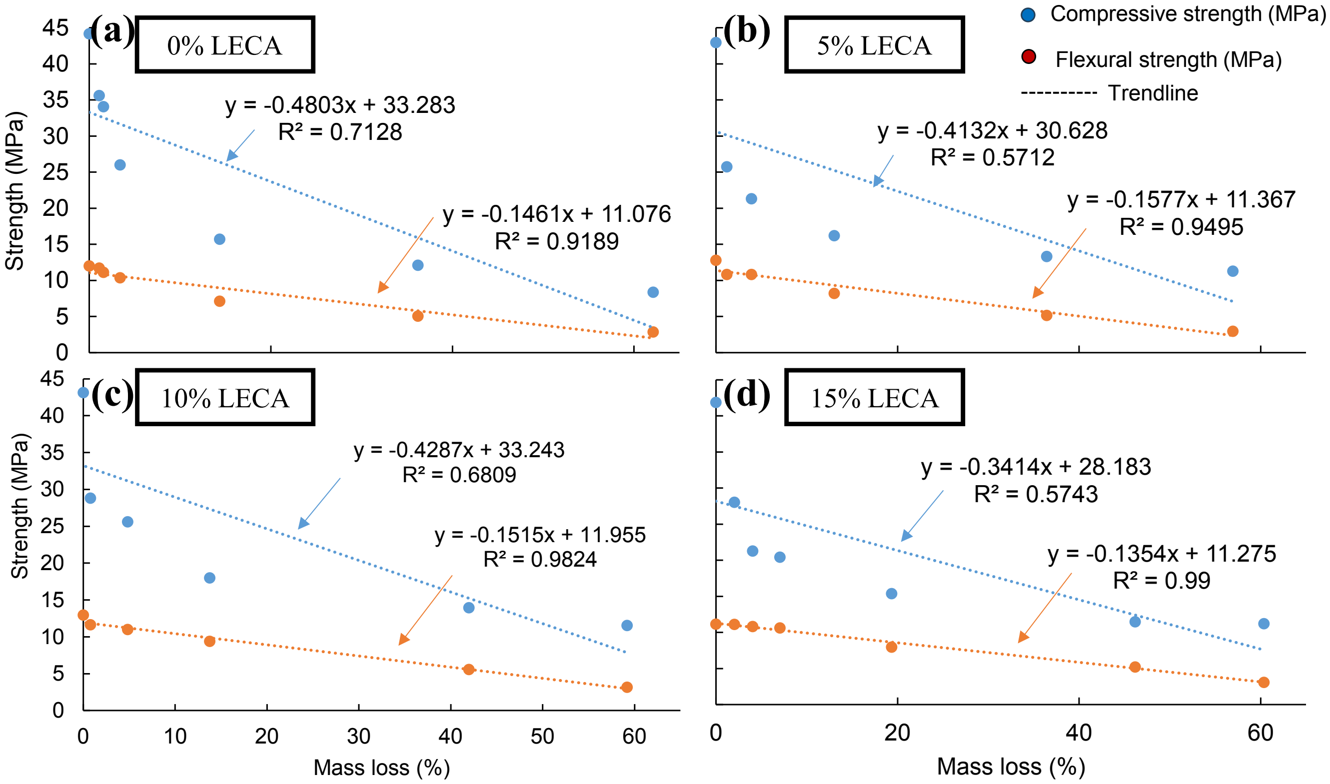

**Figure 8. Relationship between mass loss and compressive and flexural strength: (a) 0% LECA, (b) 5% LECA, (c) 10% LECA, and (d) 15% LECA.**

The mass of the control specimen without LECA was generally higher than that of the other mixtures at almost all exposure periods. This can be attributed to the fact that LECA is a lightweight aggregate, which reduces the overall mass of the mortar specimens. The mass loss of all mixtures occurred with nearly similar slopes, although the rate of mass reduction increased after 14 days of acidic exposure. As shown in Figure 7, after 14 days of exposure, specimen ML0 exhibited the highest mass, followed by specimen ML15. After 90 days of exposure, the control specimen showed the lowest remaining mass compared to the other mixtures, while the specimen containing 5% LECA exhibited the highest remaining mass. These results indicate that the incorporation of LECA in the mixture can reduce long-term mass loss of mortar under acidic conditions.

Figure 8 illustrates the relationship between mass loss and both compressive and flexural strength for different LECA replacement levels under internal curing conditions. Trend lines are provided for each dataset. In each case, a higher coefficient of determination ($R^2$) indicates a better fit and a more accurate estimation of the observed trends. Mass loss is a key factor influencing the strength behavior of mortar under acidic exposure, and as observed, an increase in mass loss percentage corresponds to a reduction in both compressive and flexural strength. Furthermore, analysis of the coefficients of determination reveals that, due to their values being close to unity, the linear trend provides a more reliable estimation for flexural strength. In contrast, the proposed linear relationship for compressive strength exhibits a comparatively weaker correlation than that observed for flexural strength.

## ٦. Conclusion

In this study, the optimal replacement level of LECA with internal curing as a substitute for natural sand in structural mortar was investigated to achieve maximum compressive and flexural strength under acidic exposure conditions. Four mortar mixtures were prepared by replacing sand with 0%, 5%, 10%, and 15% LECA. Cubic and prismatic mortar specimens were cast and water-cured for 28 days, followed by exposure to sulfuric acid with a pH of 1.5 for durations of 0, 3, 7, 14, 28, 56, and 90 days to simulate acidic environments. Compressive strength, flexural strength, mass loss behavior, and the relationship between strength reduction and mass loss were evaluated. Based on the experimental results, the following conclusions can be drawn:

1. Prior to acid exposure, the compressive strengths of all four mortar mixtures were nearly identical, indicating that replacing sand with LECA under internal curing conditions does not adversely affect the initial compressive strength.
2. Acidic exposure resulted in CSR for all specimens. However, the control mixture without LECA exhibited a greater long-term strength degradation compared to the LECA-containing mixtures, showing the highest CSR at 56 and 90 days.
3. Evaluation of flexural strength revealed that before acid exposure, specimen ML10 exhibited the highest flexural strength among all mixtures. Therefore, the use of 10% LECA as a sand replacement under internal curing conditions can be considered optimal.
4. Under acidic exposure, FSR for all mixtures, similar to the behavior observed in compressive strength. Nevertheless, the mixture containing 10% LECA demonstrated lower FSR compared to the other mixtures, indicating improved flexural performance in acidic environments.
5. Since LECA is a lightweight aggregate, mortar specimens containing LECA exhibited lower mass compared to the control specimen at most exposure periods. However, after prolonged acid exposure (90 days), the control specimen exhibited the lowest remaining mass, whereas LECA-containing mixtures showed reduced mass loss. This suggests that incorporating LECA in the mixture can mitigate long-term mass loss under acidic conditions.
6. Analysis of the relationship between mass loss and mechanical strength indicated that increases in mass loss were accompanied by reductions in both compressive and flexural strength. Moreover, due to coefficients of determination close to unity, linear relationships provided a more reliable estimation for flexural strength behavior than for compressive strength, for which the linear correlation was less representative.

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