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The effect of sand on the mechanical characteristics of gypsum-lime mortars for heritage buildings

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Abstract. The endurance and preservation of historical buildings greatly depend on the integration of lime into the mortar used for masonry linings. Therefore, conducting mechanical assessments of existing and restoration mortars is crucial to ensure their compatibility and prevent potential issues. This article emphasizes the role of sand in enhancing the efficiency and resilience of gypsum-lime mortars by examining how it influences on their mechanical properties. The main aim of this research is to provide practical guidance for the sustainable restoration and conservation of historical edifices. The study examines the mechanical attributes of gypsum-lime mortars for restoring historical structures, with a specific focus on evaluating the impact of different sand proportions (10%, 15%, and 20% by gypsum volume). Moreover, the results were scrutinized to comprehend the compositions, structural features, and compressive strength. Among the six mortar blends, the addition of 15% sand was identified as the most effective augmentation to gypsum-lime, demonstrating comparable workability. Furthermore, this proportion exhibited improved compressive and flexural strengths on the seventh day compared to pure gypsum-lime. This highlights the potential economic application and further enhancement of this locally sourced product in various finishing applications. Notably, gypsum-lime mortar infused with 15% sand exhibited optimal structural properties, particularly in terms of compressive strength.

Keywords: gypsum, lime mortar, historical buildings, Compressive strength, Shrinkage Cracking,

1. Introduction

Gypsum-lime mortars are extensively used in the restoration and conservation of historical structures due to their historical relevance and compatibility with traditional building methods[1]. These mortars provide notable advantages, such as improved workability and strong adhesion, making them suitable for maintaining the historical authenticity of heritage buildings. In the context of gypsum-lime mortars, the role of sand is pivotal in optimizing them for the restoration of heritage buildings[2]. A study focusing on lime-based mortars for restoration indicates that well-graded sand is suitable for masonry and rendering/plastering mortars, demonstrating good applicability and performance[3]. Research has shown that reducing sand particle size can enhance the mechanical strength of gypsum-cemented materials[4]. In the domain of mortar properties and characteristics, a study on alkali-activated mortar employing various binder systems revealed that the mortar's workability was influenced by both the type and quantity of binder used[5]. Similarly, another study on mortar and concrete properties utilizing machine-made sand from tunnel slag emphasized the impact of sand particle size and shape on mortar workability[6]. In summary, the effect of increasing the sand proportion in gypsum mixtures on mechanical properties may vary based on factors such as sand particle size, gypsum content, and the presence of other additives[7]. Another study on repair mortars for restoration highlights that mechanical compatibility affects the reversibility of mortar, resulting in lower mechanical properties compared to the original plaster[8]. These studies underscore that the selection of sand and its proportion in the mortar mixture can significantly influence the mechanical properties, a critical consideration for heritage building restoration. Numerous studies have explored the effects of sand on the mechanical properties of gypsum-lime mortars. Ghasan emphasized the role of sand in enhancing compressive strength and durability, underscoring the need for appropriate sand-to-binder ratios[9]. Thompson et al. investigated the relationship between sand grading and workability, emphasizing the critical aspect of particle size distribution[10]. These studies collectively stress the importance of sand in achieving the desired mechanical properties in gypsum-lime mortars. The study indicated that water-lime and sand-lime ratios significantly affected the compressive and shear strengths with the disintegration index of the shell lime mortar[11]. Nonetheless, this mortar was enhanced by incorporating glutinous rice. To ensure compatibility, the material's performance was crucial for rehabilitation[12]. Consequently, various studies have examined the effect of incorporating various components into lime-based mortars. Aalil et al. assessed the viability of reusing brick refuse to produce pozzolanic mortars[13]. Another study by Thirumalini et al. presented the influence of organic additives on the mechanical characteristics of lime mortar[14]. The study revealed that organic loading in lime mortar reduced porosity owing to filling the space between adjacent lime particles. Although a lime mortar containing a significant amount of small pores did not affect overall porosity, the organic materials strengthened the mortar. Given the need to emphasize lime compatibility with different binders, studies were conducted to compare the properties of multiple binder performances and mortars constructed with blended binders[15]. Generally, gypsum-lime mortar is mainly used for rehabilitation, and the additional impact of brick dust on blended gypsum-lime mortars has not been studied. While existing literature provides valuable insights into the effects of sand on gypsum-lime mortars, a comprehensive exploration of the influence of varying sand proportions on specific mechanical properties, such as flexural strength and porosity, is still lacking[16]. Moreover, a deeper understanding of the interaction between different sand types and gypsum-lime binders is essential to optimize mortar composition for the restoration of heritage buildings. The primary aim of this study is to thoroughly analyze the influence of varying sand proportions on the mechanical properties of gypsum-lime mortars, encompassing compressive strength, flexural strength, and porosity. The study seeks to establish the most effective sand-to-binder ratios to achieve the desired mechanical properties while preserving the authentic nature of heritage buildings. The research will involve formulating gypsum-lime mortars with different sand proportions and evaluating their mechanical properties using standardized testing procedures. Samples will be prepared with varying sand content, and tests will be conducted to measure compressive strength, flexural strength, and porosity. Statistical analysis will be employed to identify the most optimal sand-to-binder ratio for optimal mechanical performance. This study holds significant importance for the preservation and rehabilitation of heritage buildings. By identifying the ideal sand-to-binder ratios for gypsum-lime mortars, this research will contribute to the development of restoration guidelines, ensuring that the restoration materials align with historical practices. Ultimately, the study aims to enhance the durability and longevity of heritage structures, thus preserving our cultural heritage for future generations.

2. Materials

2.1 Gypsum

The gypsum powder was acquired from a local store in Mosul, primarily a gypsum production source in the northern region of Iraq. This study sieved gypsum powder using a 200 mm sieve (1.18 mm) to eliminate agglomerates and other impurities. compute the water content for the gypsum paste with the initial and final setting periods to ensure it conforms to Iraqi criteria. **Table 1** show the mechanical properties of gypsum according to Iraqi specification.

Table 1. Mechanical properties of gypsum.

Property	**Result**	**Specs. Limit.**
Fineness	5.5%	≤ 8%
Standard consistency %	45%	-

Setting time (min.)	25	≥ 8 min
Compressive strength (N/mm^2)	4.88	≥ 3 Mpa
Flexural strength (N/mm^2)	1.92	-

2.2. Lime
Powdered lime was transported from the Karbala factory, a primary source of lime production in Iraq. In this study, hydrated lime was utilised as a secondary additive to improve the characteristics of gypsum. **Table 2** show the mechanical properties of hydrated lime and **Table 3** tabulates the lime composition, the principal constituent of calcium oxide (CaO).

Table 2. Mechanical properties of hydrated lime

Property	Result
Fineness retained on sieve No 170	4%
Standard consistency %	51%
Setting time (min.)	35
Compressive strength (N/mm^2)	2.26
Flexural strength (N/mm^2)	0.98

Table 3. Chemical properties of lime

Property	Specs. Class A	Results
Calcium and Magnesium Oxides %	≥ 60	66
magnesium oxide	≥ 5	3.5
Silica, alumina and iron oxides %	≥ 25	26
Residual undissolved precipitate in hydrochloric acid except silica %	≤ 2	0.63
CO_2 %	≤ 5	2.8
Cementitious value	≤ 0.6	0.37

2.3. Sand
Construction sand was applied as fine aggregate following Zone-II (IS: 383-2016) criteria [17]. The specific gravity and bulk density of the sand were 2.66 and 1.46 g cm^{-3}, respectively. **Figure 1** displays supplementary materials.

Figrue .1 supplemental materials

3. Mix Proportions and Test Method

Gypsum, lime, and sand were combined using the mix proportion binder-to-lime mortar ratio (1:1.5). Sand was added by the gypsum volume and mixed for 3 mins to ensure homogeneity. The mixture was mixed with water and blended further for 1 min. After mixing, the cohesion was tested to determine the consistency following ASTM C191 of mixes[18]. This process was performed to select the w/b ratio (trial and error), which was 0.6 for gypsum and 0.7 for lime paste. The new mixture was cast in moulds with suitable dimensions for compressive strength casting. Compressive strength tests were investigated for three cubes (50 mm × 50 mm × 50 mm) on the seventh day in line with EN 1015-11 [19]. Each gypsum-lime mortar cube was weighed before the test, which was subsequently delivered to the compression equipment for examination. The equipment was set up such that the face of the concrete casting was perpendicular to the equipment (unit was in contact with smooth surfaces). Each result was gathered as the specimen was centred on the plate of the equipment, and the average flexural strength of three cubes following EN 1015-11 was evaluated [19].

Three prisms (40 mm × 40 mm × 160 mm) were cast and subjected to a single-point loading on the beam to determine the weekly average flexural intensity over seven days. Each mixture result was gathered, and the average strength of three prisms was considered. The ultrasonic pulse velocity(UPV) NP EN 12504-4 [20] and dry density (EN 1015–6:1999) were investigated for these prisms, which were examined for seven days [21]. This UPV technique calculated the velocity of longitudinal wave pulses travelling through the lime paste. Therefore, the UPV was measured with a direct transmission technique with an ultrasonic tester (Portable Non-Destructive Digital Tester). Each mix result was recorded, and the average velocity of three prisms was considered for the visual examination. In shrinkage cracking, the mortar samples utilised in the coating layer of the moulding test castings (300 mm × 300 mm × 20 mm) exhibited cracking and were monitored for 28 day[12], the specimens were removed from the mould. Finally, the atmospheric conditions were checked daily and placed in a laboratory with a temperature of 23 ± 2°C until the seventh day of the test. In this study, we investigated the influence of incorporating different proportions of sand (10%, 15%, and 20%) into gypsum mixtures. The constituents of the additional materials can be found in table 4.

Table 4. Mix proportion for the lime mortar (volumetric scale).

Mix no.	Hydrated Lime	Gypsum	Sand %	W/ b Ratio
M1	0	1	0	0.6
M2	1	0	0	0.7
M3	1.5	1	0	0.6
M4	1.5	1	10	0.6
M5	1.5	1	15	0.6
M6	1.5	1	20	0.6

4. Results and Discussion

4.1. Density

Figure 2 illustrates the bulk densities of gypsum, lime, and gypsum-lime mortar. The addition of sand to gypsum resulted in higher bulk density, making the sand-containing mortar denser than the lime-containing one. Figure 1 also presents bulk densities determined using hydrostatic weighing. The gypsum mortar with 20% sand exhibited the highest density due to its low porosity compared to other mortars. Concerning the absolute density of gypsum-lime mortar, mortar densities for M2, M3, M4, and M5 decreased as the sand amount decreased. Notably, the substantial density difference between M2, M3, M4, and M5 was attributed to the lower porosity of M1. The incorporation of sand into the mortar amplifies its bulk density as sand particles are denser than gypsum and lime. Although gypsum and lime slightly increase the bulk density, this effect is modest compared to denser materials like sand or aggregates. The bulk density is influenced by the sand proportion relative to gypsum and lime. A higher sand-to-gypsum-lime ratio leads to a denser mortar with increased bulk density[7]. Maintaining an appropriate balance between the sand content and gypsum-lime ratio is vital to achieve desired mortar properties, including strength, workability, and density. Different ratios result in varying bulk densities, depending on the specific composition and qualities of the sand used. In summary, the observed trends in the six mortars were primarily influenced by the materials' absolute density and porosity.

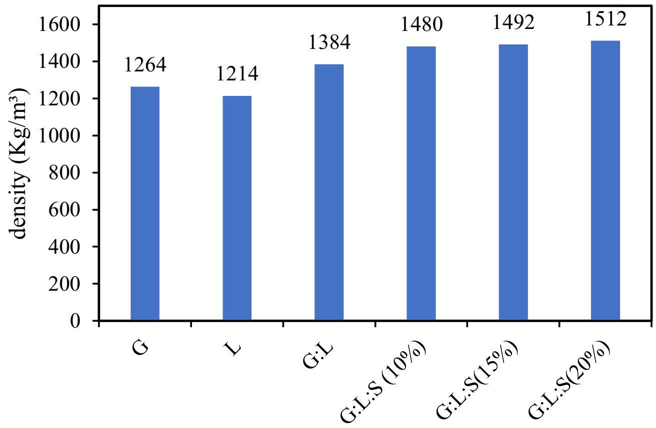


Figure 2. The relation between bulk density and mortar type

4.2. Compressive Strength

Table 5 presents the results for gypsum-lime mortar after seven days with varying sand percentages. At a modest sand ratio of 10%, the gypsum lime mortar exhibited a smoother texture. This blend demonstrated heightened compression strength compared to pure gypsum lime mortar due to improved uniformity and some fortification from the sand particles. As the sand proportion increased to 15%, the compression strength of the mortar continued its upward trajectory. The sand particles played a crucial role in occupying voids and creating a denser structure, thereby reinforcing the mortar's ability to withstand compression. As a result, the mortar achieved optimal structural robustness, yielding its highest compression strength within this range. However, at 20%, an excess of sand slightly diminished the compressive strength.

An abundance of sand disrupted the mortar's cohesiveness, consequently affecting its compressive strength. In summary, integrating sand into gypsum lime mortar heightened compression strength up to an optimal proportion (15%). Beyond this threshold, an excessive amount of sand could diminish compression strength by disrupting the mortar's cohesive structure. Hence, achieving the desired compression strength for a specific construction application necessitates a meticulous balance in the sand content[22].

Table 5. Compressive strength results for gypsum - lime mortar

Mortar Mix	**Lime**	**Gypsum**	**Sand %**	**W/b Ratio**	**Compressive strength (Mpa)**
M1	0	1	0	0.6	4.88
M2	1	0	0	0.7	2.26
M3	1.5	1	0	0.6	3.74
M4	1.5	1	10	0.6	3.82
M5	1.5	1	15	0.6	4.52
M6	1.5	1	20	0.6	4.22

4.3. Flexural Strength

The findings on the seventh day for gypsum-lime mortar mixes with various sand percentages (gypsum volume) are listed in **Table 6**.

Table 6. flexural strength results for gypsum - lime mortar.

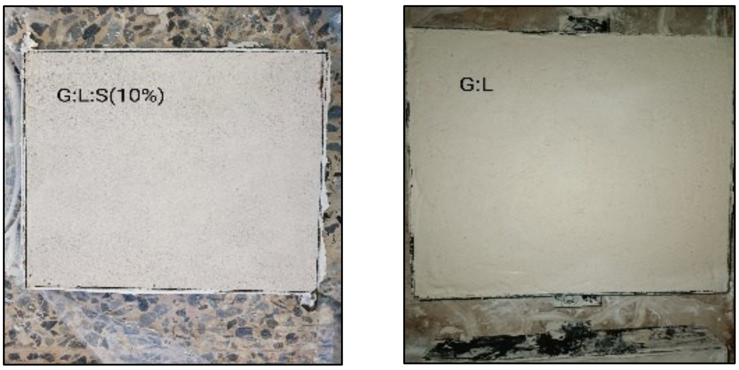
Mix no.	Lime	Gypsum	Sand %	W/b Ratio	Flexural strength (Mpa)
M1	0	1	0	0.6	1.92
M2	1	0	0	0.7	0.99
M3	1.5	1	0	0.6	1.65
M4	1.5	1	10	0.6	1.46
M5	1.5	1	15	0.6	1.62
M6	1.5	1	20	0.6	1.53

When the sand content is lowered to 10%, gypsum lime mortar displays a smoother texture and improved workability. At this level, there is a slight increase in flexural strength due to better uniformity and some reinforcement from sand particles. Further increasing the sand content to 15% results in a more pronounced enhancement of flexural strength during the initial stages. The sand particles play a crucial role in strengthening the structure, making the mortar more resilient and balanced, ultimately leading to improved flexural strength. However, at a sand content of 20%, there is a slight decrease in flexural strength. Excessive sand adversely affects the cohesion of the mortar, resulting in a less flexible structure and reduced flexural strength.

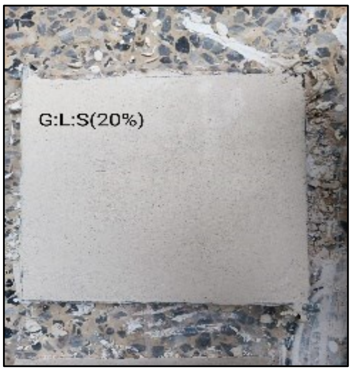
In summary, adjusting the sand proportion in gypsum lime mortar significantly influences flexural strength. Adding sand up to the optimal level (15%) maximizes flexural strength by enhancing uniformity, solidity, and bonding between particles. To sum up, varying the proportion of sand in gypsum lime mortar significantly impacts flexural strength[23].

4.4. Moulding Test (Shrinkage Cracking Test)

At 28 day of hardening, the visual inspection of mortar specimens applied as a coating layer to the surface of ceramic bricks did not reveal the shrinkage crack formations. **Figure 3** portrays the surface images of all examined mortar coverings taken after 28 day. Within 28 day, the sand added to the gypsum mixture did not cause any damage to the gypsum mixture as the sand content reduced shrinkage in all mixtures. The sand addition to the pastes resulted in a considerable reduction in shrinkage and a restriction of edge cracking. Since no cracks occurred in the sample, the lime addition produced no negative effects. Therefore, the sand addition possessed no adverse consequences, which could be applied to improve the compressive strength. Even as the compressive strength diminished, there was no observed change.



(a) **(b)**



(c)

(d)

Figure 3. (a) Surface of gypsum-lime coating specimen at 28 days. **(b)** Surface of gypsum-lime and (10%) sand coating specimen at 28 days. **(c)** Surface of gypsum-lime and (15%) sand coating specimen at 28 days. **(d)** Surface of gypsum-lime and (20%) sand coating specimen at 28 days.

Research on shrinkage in lime stucco indicates that storing lime mortar briefly can reduce shrinkage in stucco[24]. Another study on cement-lime mortars proposes that a significant sand presence decreases mortar shrinkage but compromises its strength. These investigations highlight how the sand type and quantity in the mortar blend can influence both shrinkage and strength[25]. However, more research might be necessary to explore how adding sand to gypsum-lime mortar impacts shrinkage in historical structures.

4.5. Ultrasonic Pulse Velocity

The UPV provides information on the homogeneity, mechanical properties, and crack occurrences in lime mortars. This parameter was calculated following on the seventh day.Six sample measurements were examined and recorded for each specimen type and mixture of gypsum lime mortar. Thus, little changes in this parameter were identified for all the investigated mortars, indicating that their porosity would be comparable, with minor variations. **Table 7** presents the outcome after seven days.

Table 7. Ultrasonic pulse velocity results for gypsum - lime mortar

Mix no.	**Lime**	**Gypsum**	**Sand %**	**W/b Ratio**	**ultrasonic pulse velocity(m/s)**
M1	0	1	0	0.6	1.32
M2	1	0	0	0.7	0.62
M3	1.5	1	0	0.6	1.12
M4	1.5	1	10	0.6	0.98
M5	1.5	1	15	0.6	0.93
M6	1.5	1	20	0.6	0.87

Although mortars containing gypsum and lime were hardly less porous, the data obtained from prismatic samples (see **Table 7**) implied that mortars containing lime and sand were more porous than the other mortars. This observation resulted from the high porosity of sand, which produced a high density. Additionally, the speed of the ultrasonic waves decreased as the sound transmission speed increased.

5. Conclusions

Several conclusions were determined in this study:

1. gypsum-lime and 20% sand were concluded to be the optimal high bulk density. A strong linear relationship between porosity and density was also established.
2. The inclusion of 15% sand in the mortars led to an increase in both compressive and flexural strengths, particularly pronounced in mortars made with a combination of gypsum lime and sand. The presence of sand particles within the mortar serves to fill gaps and produce a denser structure, ultimately enhancing its ability to withstand compressive and flexural forces. The sand essentially acts as a reinforcing agent, fortifying the mechanical strength of the mortar.
   Moreover, the sand particles aid in improved intertwining and adhesion among the mortar components, especially with gypsum lime. This heightened inter-particle adhesion elevates the overall coherence and robustness of the mixture, resulting in heightened compressive and flexural strength.
   Additionally, the sand particles possess inherent strength due to their mineral composition and physical attributes. When effectively integrated into gypsum-lime mortar, they serve as micro-reinforcements, further boosting the overall strength of the composite material.
3. In relation to the lack of occurrence of shrinkage cracks on the mortar surface after 28 days of setting, the incorporation of sand in the mix mitigates shrinkage. Sand, being a sturdy and stable constituent, can counteract the mortar's inclination to contract during the drying and solidifying stages. This phenomenon aids in diminishing the probability of shrinkage cracks appearing on the mortar surface.
4. all the investigated mortars acquired comparable UPVs, indicating that their global porosities would be almost identical with minor variations.

The lime mortar coatings demonstrated better mechanical characteristics overall. This study focused on evaluating various mortars for their potential in restoring masonry components within historical structures. Research delved into lime-based mortar performance concerning rehabilitation in aged constructions. The outcomes highlighted the lime mortar coatings as notably superior in terms of mechanical properties in contrast to other mortar types[1]. Another research scrutinized the physical and mechanical attributes of mortar used in the preservation of the Gediminas Castle Hill's historic retaining wall in Vilnius, Lithuania. The findings underscored that the mechanical properties of historical mortars, particularly those derived from hydraulic lime, surpassed those of mortars obtained from non-hydraulic lime[26].

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