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# Investigation of Hydraulic Binding Characteristics of Lime Based Mortars Used in Historical Masonry Structures

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**Abstract.** In the historic masonry structures, hard and large rock fragments were used as the construction materials. The hydraulic binder material prepared to keep this used material in its entirety is a different material than the cement used today. Khorasan mortar made by using aggregate and lime exhibits a more flexible structure than the concrete. This feature allows the historic building to be more durable. There is also a significant industrial value because of the use of Khorasan mortar in the restoration of historic masonry structures. Therefore, the calculation of the ideal mixture of Khorasan mortar and the determination of its mechanical and physical properties are of great importance regarding preserving historic buildings. In this study, the mixtures of different lime and brick fractions were prepared. It was determined that Khorasan mortar shows the highest compressive strength in mixtures with water/lime ratio of 0.55 and lime/aggregate ratio of 0.66. By keeping the mixing ratio constant, it was observed that the strengths of the samples kept in the humidity chamber for different curing times increased day by day. The early strength values of samples with the high lime/aggregate ratio (l/a: 0.83) were higher than those with the low lime/aggregate ratio (l/a: 0.5). For the samples with low lime/aggregate ratio, there was an increase in the strength values depending on the curing period. As the cure duration increases, a chemical reaction takes place between the lime and the brick fracture, and as a result of this reaction, the strength values are increased.

## 1. Introduction

Unlike the cement, Khorasan mortar used as a hydraulic binder and prepared with aggregate and lime has a more resilient structure in historic masonry buildings. The physical and mechanical properties of Khorasan mortar are affected by material proportions, mineralogical and textural properties. The mortar and plaster obtained by using lime were used in the construction of the buildings from ancient Greek, Roman and following periods until the cement was found. Lime mortar and plaster are obtained by mixing aggregates as binder and lime and filling material. It is also known that in the preparation of lime mortars, organic and inorganic materials are added for the purpose of improving the qualities of the lime or mortar. These raw materials, which form lime mortars are described below.

Calcareous raw materials are limestone composed of calcium carbonate ( $\text{CaCO}_3$ ) minerals. These stones are calcined by heat and are converted into calcium oxide ( $\text{CaO}$ ) as a result of the separation of carbon dioxide gas ( $\text{CO}_2$ ) from the structure. This product is called as quicklime. The calcination temperature of calcium carbonate is  $900^\circ\text{C}$  at 100%  $\text{CO}_2$  environment and 760 mm Hg pressure [1]. This temperature decreases with the decline in  $\text{CO}_2$  concentration. The quicklime ( $\text{CaO}$ ) obtained as a result of calcination is converted into calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) by reacting with water or moisture



in the air. This product is called slaked lime. It is enough to have 35% relative humidity in the air to lime slaking [2].

There are many factors that affect the quality of the lime. The physical properties of limestone, such as porosity distribution, and size of calcium carbonate crystals are the most fundamental factors that influence the reactivity of quicklime [3]. In addition to these factors, water/lime ratios, purity, particle size, temperature, mixing, purity of the water used in the mix also affect the properties of the lime.

It has been known that since the Roman and subsequent periods that the slaked lime has been used for many years without being in contact with the air. In the Roman period, it was suggested that the lime should be utilized after waiting at least three years. As the process of lime quenching prolongs, plastic properties and water retention capacity are increasing [4]. In this process, the size of the lime crystals (portlandite) is getting smaller and the surface area that reacts with carbon dioxide of the air increases and the carbonation occurs faster [5].

Aggregates are used as filling material in the construction of lime mortar and plaster. Aggregates can be classified as those that do not react with lime and those that enter reaction. Non-reactive aggregates are derived from stone quarries, streams and seas. Pozzolanic aggregates are composed of amorphous silicates and aluminates, which react with lime to make the mortars and plaster harden in damp environments and even under water. Pozzolans can be analyzed in two groups: natural and artificial. Natural pozzolans (tuff, trass, opal, etc.) are usually composed of volcanic ash [6]. Bricks and tiles are used as artificial pozzolan in the mortar and plaster of many historical buildings.

The hardening of the mortar and the plasters is the result of carbonation of the lime by carbon dioxide in the air. Carbonation can be explained by the gas-liquid-solid reaction [7]. Carbon dioxide ( $\text{CO}_2$ ) is dissolved in condensed water ( $\text{H}_2\text{O}$ ) on the surface or in the pores of the lime. In this dissolution, hydrogen ion ( $\text{H}^+$ ), bicarbonate ( $\text{HCO}_3^-$ ) and carbonate ( $\text{CO}_3^{2-}$ ) ions are formed and become water acidic. Lime ( $\text{Ca}(\text{OH})_2$ ) soluble calcium ( $\text{Ca}^{+2}$ ) ions form in the resulting acidic water. It combines with  $\text{Ca}^{+2}$  ions and  $\text{CO}_3^-$  ions to form calcium carbonate ( $\text{CaCO}_3$ ). Many factors influence the carbonation of the lime. The most important of these are the amount of water, the concentration of carbon dioxide and the gas permeability of the lime [8]. Carbonation increases with increasing carbon dioxide concentration. Carbonation is very slow in the absence of water or the presence of excessive quantities. Environmental relative humidity is another effect that affects carbonation. As relative humidity increases, carbonation increases [9]. Carbonation is on the outer surface of the lime to the inner surface. Therefore, the lime mortars and the thickness of the plasters, the lime/aggregate ratios, the aggregate distributions, the mixing and the resulting porous structure affect the carbonation.

Bricks, tiles and similar materials were mixed with lime and used in the preparation of mortar and plaster material for many historical buildings. This mortar and plaster are hydraulic and known as Khorasan mortar and plaster in Turkey. These mortars were called "Cocciopesto" [10] in Rome, "Surkhi" [11] in India and "Homra" [6] in Arab countries.

Many old masonry houses are present in Manisa-Kula. Kula houses have two or three floors with a basement used as a stable or storeroom. In general, the first floor was built with stones, and the second floor was constructed with timbers (Figure 1). However, the second-floor walls of some houses were built with stones (Figure 2). Basalt, schist, gneiss and marble stones and bricks were used as foundation and wall materials. Timbers were sometimes observed among stones in the exterior walls. Also, bricks were used as filling materials in the walls on the ground and second floors. The Ottoman house exemplifies the oldest house type known in Kula, and some of them can be dated back to the late eighteenth century. Khorasan mortar used in Kula houses, generally, includes a high volume of calcite and sand and a very low volume of brick and crushed brick. The color of the mortar is light brownish white or light gray. The brick used in mortar and walls were a reddish brown color [12].



**Figure 1.** Beylerbeyi house, second-floor built with timber [12].



**Figure 2.** Cigerciler house, whole outside walls built with stones [12].

This study was carried out to investigate the hydraulic binder properties of the Khorasan mortar obtained by using lime as the main material and fire bricks and sand as aggregates.

## 2. Materials

Lime, sand and crushed brick were used as materials in this study. A slaked lime obtained from Nuh Cement Industry Inc. was utilized in the mixes. The chemical compounds of it were presented in Table 1.

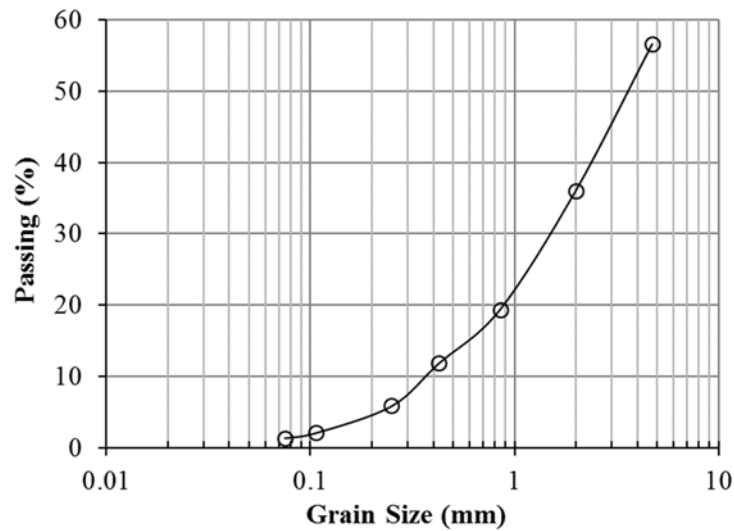
**Table 1.** Some properties of lime.

Chemical Compounds	(%)	Physical Properties	Value
Ca(OH) <sub>2</sub>	80 - 86	Density (g/cm <sup>3</sup> )	0.6
CaO+MgO	> 88	Passing #200 (%)	0.72
MgO	1 - 2	Passing #10 (%)	99.3
Dissolved	<1		
SO <sub>3</sub>	<1.5		

Standard Rilem sand used as aggregate in the mixes has the density of 1.35 g/cm<sup>3</sup> and the specific gravity of 2.56. The chemical compounds and the physical properties of the crushed brick were presented in Table 2 as well as the grain size distribution was shown in Figure 3.

**Table 2.** Some properties of crushed brick.

Chemical Compounds	(%)	Physical Properties	Value
SiO <sub>2</sub>	69.8	Density (g/cm <sup>3</sup> )	1.7
Al <sub>2</sub> O <sub>3</sub>	15.2	Silt (%)	13.7
Fe <sub>2</sub> O <sub>3</sub>	4.08	Sand (%)	41.7
CaO	1.8	Gravel (%)	43.3
MgO	1.6	Finer than no.200 (%)	1.3
SO <sub>3</sub>	0.17		
K <sub>2</sub> O	3.5		
Na <sub>2</sub> O	3		
LOI	0.85		



**Figure 3.** The grain size distribution of crushed brick.

### 3. Method

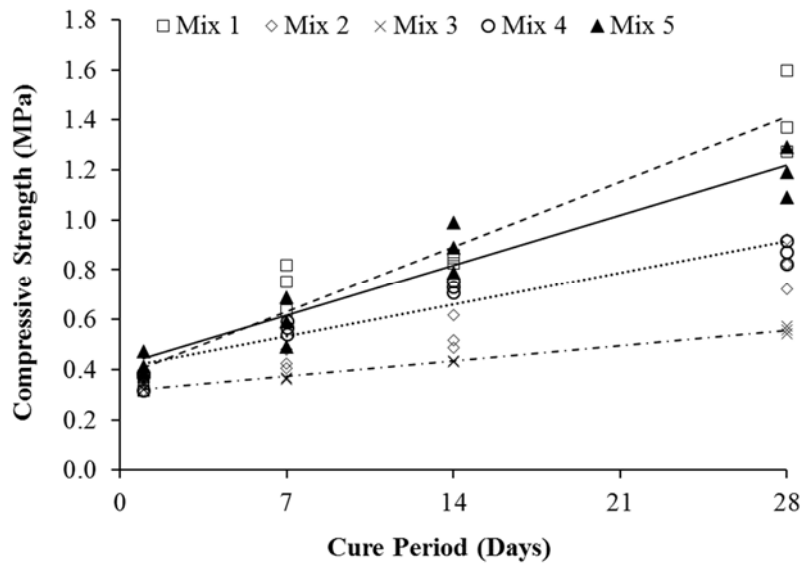
In the laboratory tests carried out within the scope of this study, water, lime, sand and crushed brick in the determined quantity and proportions; mixed with the aid of a mixer, poured into the molds of dimensions 150x150x150 mm. Five different mixes were used in the tests (Table 3). Cubic samples were cured at the periods of 1, 7, 14 and 28 days in the humidity cabinet having %80 Rh and 21°C. Then, cured samples were tested in the compressing machine having the 100kN load capacity.

**Table 3.** Mix proportions.

Mix No	Water/lime	Lime/Aggregate	Brick/Lime
1	0.55	0.67	0.75
2	0.55	0.83	0.6
3	0.55	0.5	1
4	0.6	2	0.25
5	0.55	2	0.25

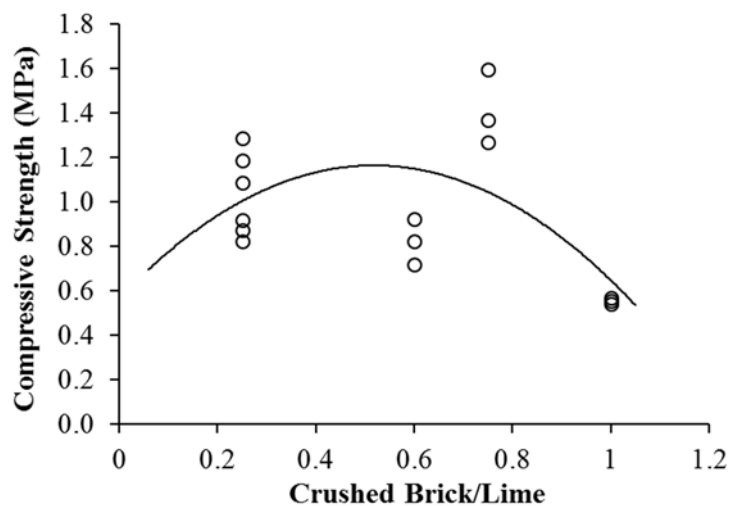
### 4. Results

The compressive strengths of the mixes were presented in Figure 4. The highest value was determined on the mix one which has 0.55 water/lime, 0.67 lime/aggregate ratio and 0.75 brick/lime ratios. The cure period is efficient on the strength values. As the cure time increased, the strength values increased.



**Figure 4.** The compressive strength of cured samples.

The ratio of crushed brick/lime is effective on the strength of the samples cured 28 days. This behavior is a sign of the cation exchange between  $\text{CaCO}_3$  (lime) and  $\text{SiO}_2$  (brick). The optimum cake brick/lime ratio was determined as 0.55 when the strength values of the samples with 28 days curing time were evaluated (Figure 5).



**Figure 5.** The variation of the compressive strength as to crushed brick/lime.

## 5. Conclusions

By results of this study, these conclusions have been drawn;

- 1) The highest compressive strength values were determined on the samples having 0.55 water/lime, 0.67 lime/aggregate ratio and 0.75 brick/lime ratios.
- 2) Cure period is very effective on the strength of the samples.
- 3) The optimum value of crushed brick/lime ratio for reaching the highest strength is 0.55.

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