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# Uniaxial compressive tests on ancient brick masonry from heritage buildings under unsaturated freeze-thaw conditions

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## HIGHLIGHTS

- An appropriate saturation degree keeps heritage masonry structure in good condition.
- Crack initiation patterns vary with stress levels and the number of freeze-thaw cycles.
- Stress levels of crack initiation vary with the number of freeze-thaw cycles.
- The microstructure may be altered the deterioration of masonry structures.

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## ABSTRACT

Freeze-thaw action, as an atmospheric impact, affects masonry by altering its original microstructures, which causes severe damage by decreasing the compressive strength of the masonry. This process, studied mostly under saturated conditions, in reality usually occurs under unsaturated conditions, which are characterized by more complex modes and have not been studied in depth before. To simulate and investigate processes and basic trends of these modes and examine the post-freeze-thaw compressive behaviors, we place our specimens (including ancient bricks and the mortar created and rebuilt masonry specimens) in an environmental chamber before performing compressive tests. We classify all specimens into eight scenarios, varying the numbers of freeze-thaw cycles and corresponding degrees of saturation. We discuss the impacts of these two factors on the compressive behaviors of the test specimens. Our results suggest that freeze-thaw cycles and degrees of saturation have combined effects on both ancient bricks and the mortar created. Under conditions of low saturation degree, freeze-thaw, as the primary factor, improves the strengths of both materials, although to a limited extent, while under conditions of high saturation degree, the degree of saturation becomes the predominant factor that results in the cracking and even failure of the materials, powered by freeze-thaw processes. Using these two factors (i.e., freeze-thaw action and degree of saturation), we summarize three different stages (or classified groups) in terms of stress-strain curves and crack development in masonry specimens based on the slopes of stress-strain curves and the rates of crack development. After studying all test results, we recommend an optimal saturation degree (approximately 50%) that is considered beneficial for ancient masonry in terms of freeze-thaw resistance.



## 1. Introduction

The entry of water into the pores of bricks and mortar causes severe damage to these materials, especially when they are under complex environmental influences. Such problems are very common in the protection of heritage buildings as water seeps easily into the bricks and mortar in a number of ways, which results in variation in the water contents as well. During the rainy season, due to the capillary phenomenon, water can be sucked into the pores of construction materials as the ancient bricks and mortar of a heritage building have been exposed to long-term rain impacts. This process results in various degrees of saturation of the pore structures, depending on the rainfall amount and duration. During the dry season, the capillary process transports water from underground, which has the same effect. As underground

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water is transported to higher elevations with more difficulty through capillary action which attenuates with increasing hydraulic height, the materials at higher elevations in the building usually exhibit lower degrees of saturation. In other words, both the materials themselves (bricks and mortar) and the water affect the quality of the structure. To study the current mechanical properties of a certain masonry structure, the degree of saturation is recognized as a critical parameter since it quantifies the water contents of the porous materials.

In addition to the presence of water, temperature is another predominant factor that facilitates the damage process, especially in some places where freeze-thaw is common since this is a time series-oriented dynamic effect. Under such situations, most porous materials have an ultimate saturation degree according to the critical saturation theory [6]. The ultimate saturation degree is a critical parameter reflecting the resistance of the material to freeze-thaw action because cracks initiate when the ultimate saturation degree is reached after a certain number of freeze-thaw cycles. In addition to the initiation of cracks, the static pore water pressure induced by freeze-thaw alters the original pore structure, causes more interior cracks, and reduces the density of the materials. Consequently, the reduced resistance to the impacts of the environment (temperature change, wind, and efflorescence, etc.) due to freeze-thaw action (upon the ultimate degree of saturation) is proven to be a function of the pore size and pore distribution [15].

Actually, for most of the bricks and mortar in ancient masonry structures, the degree of saturation is far below the ultimate degree of saturation. The degree of saturation is correlated with the location of the masonry material, the water suction capacity and the amount of rainfall. Some researchers suggest that the ultimate saturation state can be reached only after bricks are under the influence of rain for more than 13 h [9,19]. In many circumstances, the wet materials are in the unsaturated state, which means that water and gas coexist in the pores of the materials. In such cases, the volume of gas is reduced as the water is frozen and its volume increases, which mitigates some of the cracks caused by freezing, while for the saturated case, the increase in water volume (solid state at low temperature) causes immediate cracks inside the material since no extra pore space is available for the water volume to expand. Therefore, the freeze-thaw processes in saturated and unsaturated materials are different.

The existing literature focuses mainly on saturated freeze-thaw, which is the simplest case, so this literature is somewhat unrepresentative of the unsaturated cases. Even the General Administration of Quality Supervision [2] documents merely the specifications of saturated freeze-thaw. In addition, saturated freeze-thaw experiments are reported in most of the studies on the durability of clay bricks [24,10,13,19,20], which is a widely accepted term for describing the resistance of the masonry structures to time series-oriented damage. Although the literature after the 1960s started considering the freeze-thaw-induced damage due to ice crystallization [17,7], very few studies are found that focus on the mechanical performance during unsaturated freeze-thaw, although some do mention that water content (equivalent to the degree of saturation herein) and the number of freeze-thaw cycles play critical roles in the durability studies of masonry materials [16,18].

The masonry structures that we study have been under the influence of long-term unsaturated freeze-thaw action because of the unique climate conditions at their locations: temperate continental climate or temperate monsoon climate. These climate conditions have several features. First, the temperature varies significantly throughout the year. For instance, the reported annual average temperature of these regions is 9.7 °C, while the historical lowest and highest temperatures are −30 °C and 40.1 °C, respectively [26]. Furthermore, the annual rainfall is low (the average annual precipitation: 580 mm) and randomly distributed. Lastly, winters are chilly and dry (average temperature: −13 °C; average humidity: 46%). All these features are quite typical in the region where the Yellow River flows, an area that is also usually recognized as the origin of Chinese civilization and thus has many masonry heritage buildings. These climate features are believed to be the inherent reasons for the unsaturated freeze-thaw state of the pore structures. This paper primarily studies the ways in which the mechanical properties of the bricks and mortar obtained from this area change under the influence of unsaturated freeze-thaw cycles. Our research aims to provide theoretical and experimental support as well as constructive suggestions for the durability evaluation of the masonry structures in the heritage buildings still in use.

## 2. Specimen preparation and apparatus

### 2.1. Specimen preparation

There are four types of specimens in this study: ancient brick specimens, mortar specimens, compressive masonry specimens and shear masonry specimens. The ancient brick specimens, which were produced by baking techniques and are used for the mechanical tests, are obtained from the dismantled façades of ancient residential houses in Shanxi Province, China (Fig. 1a). The dimensions are 280 × 140 × 70 mm, and the houses were built in the Third Year of Daoguang, Qing Dynasty (the year 1823). Thus, these ancient bricks, with a saturation coefficient of 0.89, have approximately 200 years' history, and the chemical compositions of the brick specimens are listed in Table 1 (results from X-ray fluorescence analysis tests). According to the composition of ancient mortar, we create the mortar specimens, which are used for the mechanical tests, with materials such as sands and lime that are produced in recent years. To obtain these compositions, we observe the microstructure of the mortar (Fig. 1c) with a Zeiss (Stemi-2000-C) microscope and determine that the primary components of the mortar are lime and fine sands. In addition, we treat the mortar from the ancient residential houses by acid (1:3 diluted hydrochloric acid) and alkali (saturated sodium carbonate) methods for separating $CaCO_2$, hydraulic component ($SiO_2$, $Al_2O_3$, $Fe_2O_3$ and other resolved components in the weak alkali solution) according to the approach of Wisser and Knoefel [25]. The $CaCO_3$, $SiO_2$, $Al_2O_3$, $Fe_2O_3$ and aggregate are separated step by step. Based on the popular maintenance technology for ancient masonry structures in China, we use natural hydraulic lime (NHL2) from Germany, the chemical composition of which is listed in Table 1, and fine sand from northern Suzhou in China to create mortar, which includes more than 85% silicon content by weight. In the created mortar (Fig. 1d), the ratio of NHL2 to sand is 3:7 by weight. The masonry specimens are configured according to Chinese Standard of Masonry mechanical test methods (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2011). The ancient bricks are immersed in water for two hours before construction. With 10 mm-thick mortar joints, the compressive masonry specimens are created with dimensions of 425 × 280 × 870 mm (Fig. 1e and f).

### 2.2. The environmental chamber

As indicated earlier, the environmental chamber (dimensions: 4000 × 3000 × 3000 mm) is a totally automatic controlled parameter machine used to simulate the natural environmental influence on bricks, the created mortar and masonry specimens. The natural environmental chamber has the functions to simulate temperature, rainfall, $CO_2$, humidity, sunshine, ultraviolet radiation and