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Thermal and hygric expansion characteristics of mortars and bricks used in the dome structures of Turkish Baths from 14th and 15th centuries

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HIGHLIGHTS

- Thermal and hygric expansion behaviors of bricks and mortars from historical dome structures were studied.
- TECs of the mortars and bricks from the same dome structure are found to be within tight limits.
- The displacements of mortars and bricks due to increasing RH are comparable within the same structure.

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ABSTRACT

Thermal and hygric expansion characteristics of mortars and bricks from the dome structures of three Turkish Baths from 14th and 15th centuries were investigated. The linear thermal expansion coefficients of the mortars and bricks were determined in the temperature range from −10 °C to 50 °C and hygric expansion characteristics of the same samples were studied in the relative humidity range from 30% to 80%. The results showed that the thermal and hygric expansion characteristics of mortars used in the dome structures of the studied baths are very similar to those of bricks used within the same structure. The thermal expansion coefficients of the mortars are 2.5% to at most 10% greater than the bricks of the same dome. The linear displacement of the mortars and bricks due to relative humidity changes are less pronounced in comparison with the displacement due to thermal changes, but similarity in the expansion trends in between the mortar and bricks of the same structure is also observed for the hygric expansion test results. Since movement of the materials resulting from cyclic changes in temperature or relative humidity may cause stresses at the interfaces where different materials are in contact, eventually resulting in cracks and detachments, it is important to consider the thermal and hygric expansion behavior of the original materials during the selection of repair materials to be used in the conservation works of these dome structures.

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1. Introduction

The original building materials used in traditional Turkish Baths were mainly cut stone, rubble stone and brick as the main constructional units and generally lime mortar as the binding material. Bricks and lime mortars in these structures were generally used to form a homogeneous unit acting together against several structural inputs such as the stresses arising from the dead load of the structure, movements due to soil settlements or seismic loads throughout its lifespan [1,2]. Mortar between the brick units also provide a cushion to distribute the loads evenly particularly with soft bricks [2]. Studies on historical masonries show that the mortar within a masonry exhibits similar physical and mechanical characteristics with the materials they were used with, making the structure to behave uniformly against physical and environmental stresses [3–5]. Several studies revealed that mortars used with bricks for the construction of historical upper structures were prepared with higher percentages of lime and aggregates with lower density to match the physical and mechanical properties of brick units [3,5]. The compatible nature of these materials is one of the important factors contributing to the long term durability of these structures. Thermal and hygric expansion characteristics are important parameters to consider for defining the compatibility between materials which are to be used together. Since, mortar and bricks in a structure are exposed to the variations in atmospheric conditions like temperature and relative humidity together, incoherent

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movements of the materials in these structures due to changes in ambient conditions are expected to cause stresses at the contact points of these materials eventually causing failure. Especially for the dome structures, homogeneity of the construction and coherent behavior of the materials constituting the structure against changes in ambient conditions are crucial for the structural stability and long term durability. In addition, thermal and hygric expansion behavior of the materials are particularly important for bath structures, since these structures are exposed to extreme variations in temperature and relative humidity on a daily basis during their lifetime. It is therefore important to have detailed knowledge about the parameters that define the compatibility of mortars and bricks used in these structures in order to understand the reasons of their durability in time. The information revealed by the characterization studies of mortars and bricks has also vital importance for the selection of materials to be used for the repair works of these structures in order to sustain the structural integrity and homogeneity of the domes minimizing any negative outcome.

Although there are several studies on the basic physical, mechanical properties and raw material characteristics of mortars and bricks used in historical dome structures [3,6–9] and several authors have studied the thermal and hygric expansion characteristics of contemporary cement mortars, lime mortars and plasters [10–13], the research on the thermal and hygric expansion properties of mortars and bricks used in the dome structures of historical buildings is non-existent in literature to the extent of authors' knowledge.

This study focuses on the expansion behaviors of mortars and bricks used in the dome structures of historical Turkish Baths (14th and 15th centuries) against temperature and relative humidity changes.

2. Experimental

2.1. Samples studied

Mortar and brick samples from the dome structures of three Turkish Baths dating back to 14th and 15th centuries were collected. Two parallel samples were studied from each dome structure. The names and the locations of the baths and the sample codes are given in Table 1.

2.2. Bulk density, open porosity and water absorption capacity analyses

Bulk density, open porosity and water absorption capacity of the samples were determined by using the standard gravimetric method based on dry, water saturated and water immersed weight of the samples [14,15]. Samples were initially oven dried at 60 °C to constant weight, M_d and then vacuum-saturated with water for at least 24 h at a pressure of 0.1 atm and weighted as M_s. The samples were then weighted immersed in water, M_i. The density, d and percent porosity, P and water absorption capacity, A_w of the samples were calculated according to the following equations:

$$d = \frac{M_d}{(M_s - M_i)\rho_w^{-1}}$$

$$P\% = \frac{M_s - M_d}{M_s - M_i} \cdot 100$$

$$A_w\% = \frac{M_s - M_d}{M_d} \cdot 100$$

Table 1
Names and locations of baths and description of the samples studied.

Name	Location	Sample	Sample code
Yahşi Bey Bath (15th century)	Urla – Turkey	Brick	YB
		Mortar	YM
Hersekzade Bath (15th century)	Urla – Turkey	Brick	HB
		Mortar	HM
Çukur Bath (14th century)	Manisa – Turkey	Brick	ÇB
		Mortar	ÇM

where ρ_w is the density of the liquid used for the experiment which is water (ρ_w = 0.997 g/cm^3) in this case.

2.3. XRPD analyses

To determine the mineralogical phases in the mortars and bricks, X-ray powder diffraction analyses were performed using a diffractometer with a solid-state detector. Analyses were done using Cu Kα radiation with the instrument operated at 40 keV and 40 mA. The XRPD traces were recorded in the 3–70° 2θ range.

2.4. Thermal expansion properties

Linear thermal expansion coefficients of the studied materials were determined by measuring the length changes due to increase in temperature by using a system consisting of two LVDT (linear variable differential transformer) sensors connected to a data acquisition unit which is controlled by a data logger software installed on a standard computer. The length equivalent of the voltage difference due to core displacement of the sensors were calculated by measuring the voltage change corresponding to a 100 μm standard gage traceable to NIST (National Institute of Standard and Technology). The experiments were carried out in a programmable climatic chamber. The temperature range was selected considering the temperature data gathered from a traditional Turkish bath (currently in use) for 24 h in different times of the year. The temperature in this bath varied from a minimum of 10 °C to a maximum of 40 °C. However, the experimental limits were selected in a wider range (−10–50 °C), because the studied structures are also exposed to the atmospheric conditions which vary from a minimum of −10 °C to a maximum of 45 °C throughout a year in the region where they are located. A temperature gradient was created by increasing the temperature at a rate of 0.20 °C/min from −10 °C to 50 °C during the test period for the determination of thermal expansion behavior of the samples within the selected temperature range. The temperature and LVTD sensor readings are simultaneously recorded every minute. The data is then used to plot a graph of linear displacement versus temperature for every sample. TECs (thermal expansion coefficient) of the samples were then calculated from the linear regression of the plotted displacement data against temperature, using the following equation:

$$\alpha_T = \frac{1}{L_{0,T}} \cdot \frac{\Delta L}{\Delta T}$$

where $L_{0,T}$ is the length at a reference temperature, ΔL is the difference in length due to change in temperature and ΔT is the temperature difference.

2.5. Hygric expansion properties

Hygric expansion due to increase in ambient relative humidity (RH) was determined using the same measurement system but in isothermal conditions. The RH data gathered from the traditional Turkish bath mentioned before showed that the relative humidity values inside the bath vary from 30% to 98%. However, a controlled RH% gradient in time were created by programming the climatic chamber to increase RH% from 30% to 80% (at a rate of 10%/4 h), because the reliability of the programmable chamber used for adjusting relative humidity was degraded above RH 80%. The temperature was kept constant at 30 °C. The relative humidity and LVTD sensor readings are simultaneously recorded every minute. The results were plotted as a graph showing the increase in the length of a sample per unit length of the sample with increasing ambient relative humidity.

3. Results and discussion

In order to have some basic information about the physical characteristics and the composition of the studied materials bulk density, open porosity, water absorption capacity tests and XRPD analyses were performed.

The basic physical properties of the studied samples are given in Table 2. The bulk densities of mortars and bricks are between 1.61–1.72 g/cm^3 and 1.80–1.82 g/cm^2 respectively. The open porosities are in the range of 31–35% for the mortars and 27–31% for the bricks. It can be observed that the bulk densities of the mortar and brick samples from the same structure are within a small range. This can also be observed for the porosity values of the mortars and bricks. Water absorption capacity values of the mortars and bricks vary between 19–21% and 15–17% respectively.

The mineral phases detected by the XRPD analyses are given in Table 3. In all mortar samples calcite is the main mineral phase observed indicating the use of lime as the binder. Quartz is the

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