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Effects of high temperature on physico-mechanical properties of Turkish natural building stones

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ABSTRACT

It is known that fire and high temperatures cause degradation of natural building stones. There are many studies focused on the effect of high temperature on physico-mechanical properties of sandstone and granites while there are a few insufficient studies on limestones and marble. Almost all of the studies performed on limestone and marble are established at temperatures lower than 1000 °C and just focused on investigating some of the physico-mechanical properties of natural building stones and therefore some of the physical and mechanical properties of limestones and marbles exposed up to this temperature are not studied in detail. That condition cannot explain how the properties of marble and limestone change with high temperatures, which are widely used in many areas of our lives as building materials.

The aim of this study is to investigate the changing of physico-mechanical properties of natural building materials including limestone and marbles exposed to different temperatures ranging from room temperature up to 1000 °C in the oven. For this purpose, samples were exposed to the heat separately starting from 200 °C, gradually 400, 600, 800 and 1000 °C and then some physico-mechanical properties of them and reference sample at room temperature were determined. The results obtained from the tests were analyzed in detail in terms of criticality of temperature degree, positive or negative effect of temperature rise, reusability of the building stone exposed to heat.

As a conclusion of the study, important results are given in many aspects such as, usage areas of fire exposed natural stones, safety precautions at usage areas in addition to gained properties of natural stones due to temperature.

1. Introduction

Natural stones are widely used in all areas of our lives. Exact properties of the natural stones must be known especially for constructing structures such as, buildings, bridges, and tunnels. Via this method safe and healthy living areas could be created. Besides knowing the most physico-mechanical properties of natural stones, it is also required to define how natural stones are affected by the heat which is an important factor.

In many fields, such as energy, geology, civil engineering, the disposal of highly radioactive nuclear waste, the underground storage and mining of petroleum and natural gas, the development and utilization of geothermal resources, the safety of drainage and comprehensive utilization of coal seam gas and the post-disaster reconstruction of underground rocks engineering are all related to the strength and deformation characteristics of rocks under high temperatures (Liu and Xu, 2013).

It is important to predict the behavior of natural stones, which are located around high temperature and heat sources, against the temperature to take necessary security measures with estimating the damage. The physical, mechanical, chemical and petrographical properties of rock, which are used as building materials, are important from the aspect of their uses in our daily life (Karaca et al., 2010).

Marble is a material that is constantly used in building, either for structural (columns, floors, etc.) or decorative purposes (frieses, reliefs, statues, etc.). It is a noble material of particular beauty and easy manipulation, but it is susceptible to alteration by natural atmospheric agents or others resulting from urban and industrial activity (Rodriguez-Gordillo and Saez-Perez, 2006).

Rocks are composed of minerals, bounding matrix, and cracks and pores. The geometry and density of the cracks and pores are the main controlling parameters for the physical properties of rocks (Darot and Reuschlé, 2000; Yavuz et al., 2010). In engineering rock structures, temperature variation is one of the primary factors influencing the integrity and physical properties of rocks. It is responsible for the changes in microstructure of the rock by inducing new crack and micro crack development and so, for the increase in void space volume (Chaki et al., 2008).

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Cracks, crusts and spalling were observed on the blocks following the fire hazard. One should note that the term crack refers to discontinuities formed by thermal gradients within the marble blocks during the fire (Koca et al., 2006).

Fire disaster related changes in the petrological and petrophysical properties of the building materials can often lead to stability problem. It is important to establish the effect of fire and high temperature on the building structure, including natural stone. The walls of a building must necessarily attain a high temperature in a fire and suffer serious deterioration in strength and stability. Natural stone can be seriously affected in building fires, so it is useful to ascertain on which occasions the structure can be restored without replacement of stone and when it is necessary to include new stone material to maintain the structural integrity of the building (Hajpál, 2002).

The calcinations of calcite from 800 °C may constitute the main effect generated by fire, as both the transformation from calcite to calcium hydroxide and the subsequent hydration of calcium hydroxide involve important volume changes that may alter the internal structure of the stone.

$$CaCO_3 + HEAT \rightarrow CaO + CO_2 \uparrow$$

$$CaO + H_2O \rightarrow Ca(OH)_2 + HEAT$$

These materials generally do not spall severely because the grains sit in a matrix and the stone can to an extent ‘absorb’ the stress produced by fire. Dense materials, such as granites or marble, experience physical breakdown due to the micro-cracking generated by the thermal expansion of minerals. The absence of a matrix, which in more porous materials absorbs the stresses generated by the expansion of mineral grains, increases the likelihood of mechanical breakdown. The very low porosity also favors this kind of disintegration due to the denser packing of minerals with different thermal and structural properties in the stone. It has been observed that, independent of the stone type, the lower the initial porosity the greater the porosity increase generated during fire—changes up to 13 times the initial porosity have been reported in building stones with low porosity. In addition to this, calcareous stones undergo severe processes of physical destruction in zones affected by fire above 800 °C due to the calcination of calcite (Gomez-Heras et al., 2006, 2009; Ozguven and Ozcelik, 2013).

The most catastrophic change occurred in limestone cores, beginning to take place above 600 °C due to calcinations processes. Nine out of 10 Tardos limestone cores exploited during the 600 °C tests. Above 600 °C test, Süttő travertine samples were found undestroyed at the end of the test, but the samples crumbled after some hours exposed to air as a result of the volume increment produced by the reaction of CaO with air moisture to form $Ca(OH)_2$ (portlandite). This process has been previously reported as a result of high temperature testing of stones containing calcite (Chakrabarti et al., 1996; Török and Hajpál, 2005; Gomez-Heras, 2006; Gomez-Heras et al., 2006).

Researchers investigating the effects of different temperatures on natural stones have demonstrated different features of the natural stones. Some of these studies such as Blackwelder (1926) heating igneous rocks at different temperatures up to 880 °C as the presence of empirical observations or researchers such as Allison and Bristow (1999), Gomez-Heras et al. (2004), McCabe et al. (2007a) studied the weathering of rocks by the fire simulation.

The most serious studies about the effect of temperature on the sandstones were made by Mahmutoglu (1998), Hajpál (2002), Hajpál and Török (2004), Gomez-Heras et al. (2004), McCabe et al. (2007a), McCabe et al. (2007b), Gomez-Heras et al. (2008), McCabe et al. (2010). Authors examined the changes occurred in sandstones by observational and experimental studies.

Darot and Reuschlé (2000), Reuschlé et al. (2006) and Chaki et al. (2008) investigated the micro-fractures and thermal damage in the studies done on granite samples which were exposed to temperatures up to 600 °C.

Although the subject which the effects of temperature on the natural stones have been studied by different researchers, there are less number of articles that try to explain the changes of the stones by performing extensive physical and mechanical tests at very high temperatures. Studies have often tried to explain the behavior marble and limestone have shown against the heat, such as; investigation on degradation of historical buildings (Gomez-Heras et al., 2006; Koca et al., 2006; Rodriguez-Gordillo and Saez-Perez, 2006); or heat cycles with heating to 80–100 °C and cooling to −15–20 °C by examining a small number of samples (Malaga-Starzec et al., 2006; Yavuz and Topal, 2007; Lam dos Santos et al., 2011) or such as Yavuz et al. (2010) investigating some properties of heated samples up to 500 °C.

Ozguven and Ozcelik (2013) investigated the effects of different degrees of temperature from room temperature up to 1000 °C (room temperature, 200, 400, 600, 800, 1000 °C) on marble and limestone by using the aspects of change in color and whiteness, polish reception, daily physical change, pH and temperature variations of the cooling solution which was prepared from the cooked samples at 800 °C and 1000 °C. They found that natural stones' structure becomes damaged and/or changes, brakes down, pours or cracks when heated above 800 °C. They also mentioned that natural stones that face this amount of heat under atmospheric conditions, crack, fragmentize, spall and disperse generally.

The effect of temperature on marble was investigated by Liu and Xu (2013). They carried out dynamic mechanical experiments on marble under different temperatures and different impact loadings by using the high temperature split Hopkinson pressure bar (SHPB) experimental system. Their experimental results show that the stress–strain curves under impact loadings and different temperature show the same change trend below 800 °C. When temperature exceeds 800 °C, the densification stage prolongs, the curve moves towards right quickly, the slope decreases and the yielding stage extends evidently. The dynamic mechanical characteristics of marble take on obvious temperature effects.

Brotóns et al. (2013) investigated the effect of the temperatures between 105 and 600 °C on the physical and mechanical properties of a porous rock namely calcarenite including porosity, ultrasonic wave propagation, uniaxial compressive strength, young modulus, Poisson's ratio and slake durability tests. Their tests were carried out under different conditions (i.e. air-cooled and water-cooled) in order to study the effect of fire off method. The results show that uniaxial compressive strength and elastic parameters (i.e. elastic modulus and Poisson's ratio), decrease as the temperature increases for the tested range of temperatures. Slake durability index also exhibits a reduction with temperature. Other physical properties, closely related with the mechanical properties of the stone, are porosity, attenuation and propagation velocity of ultrasonic waves in the material. All exhibit considerable changes with temperature.

Sengun (2013) investigated the influence of temperatures ranging from 105 to 600 °C on the physical and mechanical properties of six carbonate rocks (two marbles, two low-porous limestones and two high-porous limestones). It was found that the values of bulk density, P wave velocity, uniaxial compressive strength and modulus of elasticity, Brazilian tensile strength and Shore hardness decreased to different extents, while apparent porosity increased under the influence of heat up to 600 °C. The results indicated a maximum decrease of 62–82% in modulus of elasticity and the least reduction of 1.2–2.7% in bulk density of carbonate rocks. Moreover, the uniaxial compressive strength, Brazilian tensile strength, P wave velocity and Shore hardness values decreased by 27–51%, 28–75%, 36–69% and 10–40%, respectively. Moreover, increase in apparent porosity values of tested rocks with very high porosity was the least, whereas the apparent porosity values of low-porous rocks increased up to ten times of initial value.