Ivanka Netinger, Ph.D. in Civil Engineering
Faculty of Civil Engineering Osijek
Crkvena 21, 31 000 Osijek
Phone: 031-540-082 Fax: 031-540-071
E-mail address: nivanka@gfos.hr

Martina Vračević, M.Sci. in Civil Engineering
Civil Engineering Institute of Croatia
Drinska 18, 31 000 Osijek
Phone: 031-253-125 Fax: 031-253-109
E-mail address: martina.vracevic@igh.hr

Robert Bušić, the first year student of graduate study level
Faculty of Civil Engineering Osijek
Crkvena 21, 31 000 Osijek
Phone: 031-540-070 Fax: 031-540-071
E-mail address: robert.busic@gmail.com

BRICK AND MORTAR OF SUFFICIENT DURABILITY – THE INVESTIGATION AND RESULTS

OPEKA I MORT DOSTATNE TRAJNOSTI-ISTRAŽIVANJA I REZULTATI

ABSTRACT

Historical buildings are subjected to processes of deterioration which threaten the future of the architectural heritage of many cities around the world. When repairing damaged buildings, it is necessary to pay attention to ensure their sufficient durability by using building materials of sufficient durability. This paper analyzes the durability properties of brick produced in two ways (handmade and machine-made) and fired at two temperatures (1000 °C and 1050 °C). Water absorption, initial rate of water absorption, net and gross dry density and saturation coefficient were monitored on the final products. The goal of this research paper is to find out the optimum ways of making and firing temperature of bricks that will result in bricks of sufficient durability intended for use in historic buildings.

Keywords: *brick, durability, water absorption, initial rate of water absorption, net and gross dry density, saturation coefficient, compressive strength.*

SAŽETAK

Povijesne građevine podvrgnute su procesima propadanja koji predstavljaju prijetnju budućnosti arhitektonske baštine mnogih gradova diljem svijeta. Prilikom sanacije oštećenih objekata, potrebno je obratiti pažnju na osiguranje dostatne trajnosti konstrukcije, i to upotrebom građevinskog materijala dostatne trajnosti. U ovom radu su analizirana trajnosna svojstva opeke proizvedene od tri različite sirovine, izrađene na dva načina (strojno i ručno) te pečene na dvije temperature (1000 °C i 1050 °C). Na gotovim proizvodima praćeni su upijanje vode, kapilarno upijanje vode, bruto i neto volumna masa te koeficijent zasićenja. Cilj istraživanja je iznalaženje optimalnog načina izrade i temperature pečenja opeke koji će rezultirati opekom dostatne trajnosti namijenjene za ugradnju u povijesne građevine.

Ključne riječi: *opeka, trajnost, upijanje, kapilarno upijanje, bruto volumna masa, neto volumna masa, koeficijent zasićenja*

1. Introduction

Nowadays, the durability of buildings has become one of the most important problems of construction engineering. Often the basic properties of buildings become weaker from the designed ones after a few years already. Historical buildings are subjected to processes of deterioration which threaten the future of the architectural heritage of many cities around the world. There are many causes for the deterioration of the architectural heritage that manifest themselves in a complete or partial demolition of facilities, additions and reconstructions, change of purpose and similar. Most significant mechanisms of masonry building deterioration are (Radić, 2010.):

- salt crystallization,
- water solubility,
- damages due to the impact of freezing/thawing,
- biological factors and
- mechanical damages.

In order to prevent or moderate aggressive impacts from the polluted atmosphere and other mechanisms which damage building elements, the maintenance and protection of such buildings includes, besides mechanical and chemical cleaning, implementing various preservatives and replacing certain specific parts or whole surfaces inside of the building. Unfortunately, in practice many reconstructions of buildings are being carried out not taking into account that the construction material is a part of the construction into which it is placed and that the construction properties directly depend on the properties of the material which is placed into it, as well as on the mutual interraction of the materials in the construction. When it comes to mortar, lime mortar and lime-cement mortar, although less solid, is considered to last longer than cement mortar. This type of mortar is porous, it loses water quickly and is less subjected to damages due to freezing/thawing (Boynton, 1989.)

The durability of brick is much more complex and depends on many parameters in the brick production process. The goal of this research is to find out the optimum ways of making and firing of brick, which will result in brick with sufficient durability intended for use in historical buildings. With this goal, series of bricks have been produced implementing two ways of production and fired at two different temperatures in an electric kiln. During the drying and firing process, shrinkage has been monitored as an important parameter which has to be taken into account during the mould-making for machine-made bricks and handmade bricks in the initial stage of the production of this building element. In brick samples, the durability properties have been tested and preliminary conclusions have been reached on the optimum process of producing brick intended for the recovery of historical buildings. Although it is not a durability parameter, the compressive strength of the brick was monitored as well.

2. Durability of bricks

2.1. The impact of the production process on the durability of bricks

Normal brick for brickwork construction from nowadays manufacturing is not suitable with its measurements and appearance for the recovery of historical buildings. Therefore, smaller series of bricks are produced for this purpose in specialised factories/manufacturies in one of the two following ways:

- machine-made, with hand finishing of the brick surface in order to obtain the appearance of an „old“ brick, or
- handmade.

The main difference between machine and hand manufacturing lies in the porosity of the manufactured brick. The total volume of pores is bigger in machine-made bricks in comparison to handmade bricks. At the same time, during the machine-making process, pores of 0,1 µm up to 1 µm in diameter - medium pores (Larsen, 1995.) are formed. Pores obtained this way are parallel with the direction of the raw material extrusion, they are horizontal and not visible on the bare surface of the product and they turn the homogenous raw material into an anisotropic final product. The result of the above mentioned is a product with less resistance to the freeze-thaw processes. Pores with a diameter bigger than 1 µm (coarse pores) are easily filled with water and emptied, which enhances the durability properties of the brick (Kung, 1985.). Fine pores (of less than 0,1 µm in diameter) have a very low impact on the resistence of the brick to freeze-thaw cycles because water freezes in them only at very low temperatures. Actually, medium pores are most subjected to the freeze-thaw effects because they are mostly filled with water, which dries up slowly in the pores. Therefore, the aim of brick manufacturing is to obtain the smallest proportion of medium size pores. But in handmade production the distribution of pores is mostly in the interval between 0.1-10 µm (Larsen, 1995.) (with a smaller proportion of pores in the range of 0,1-1 µm than in cases of machine-made bricks), and the pores are evenly placed on the cross section, which results in smaller deviations of the new product characteristics and in longer durability of the bricks.

After being manufactured, bricks are properly dried. The way of drying the brick has to be adequate in order to allow a complete loss of moisture in the product with minimum mechanic defects such as cracks.

Besides the production process, the size and system of pores which will be formed in the kiln is affected by the temperature of firing. According to (Ikeda, 2004.), for samples fired at a temperature of 900 ºC the largest amount of pores of 0.1-0.5 µm and those of 100 µm in diameter is created. At 1000 ºC, pores of 1-2 µm in diameter are mostly created and at the same time the amount of created pores of 100 µm is reduced. At 1100 ºC, the growth of pores of 1-2 µm in size is quickly reduced, whereas at 1200 ºC, the growth of pores of 0,1-0,5 µm in size increases. With regard to the previously described effect of the size of pores on the brick resistance to freeze-thaw cycles, the firing temperature of bricks between 1000 and 1100 ºC will result in the size and system of pores that will ensure the durability of bricks.

2.2 Durability parameters of bricks

Parameters for assessing the durability of bricks can be divided into indirect and direct. Into the category of indirect parameters can be included: water absorption, initial rate of water absorption, soluble salt content, pores structure and the saturation coefficient. The direct parameter, and the only parameter for assessing the durability of bricks according to the European legislation, is considered to be their resistance to freeze-thaw cycles. And while other here mentioned terms are explained in standards that these properties cover or are already explained in the text, the saturation coefficient is a quite unexplored parameter. The saturation coefficient represents the amount of absorbed water in a sample, which has been strained for 24 hours, and the amount of absorbed water after sinking in boiled water, which lasts for 5 hours (Kung, 1985.). Actually, the saturation coefficient determines the correlation of pores that are easily filled with water and the total volume of pores. Regarding all the above mentioned, the saturation coefficient becomes the indicator of free space in the volume of pores, which remains free after they are filled with water and it can also serve as accommodation for the volume of water caused by freezing.

According to that, materials with a higher water absorption refer to a higher proportion of pores with a larger diameter. Higher initial rate of water absorption indicates bigger surface pores, i.e., it defines liquid movements (water and salts) inside the material. The initial rate of water absorption is inversely proportionate to the diameter of the pores, that is, the smaller the diameter of the pores, the higher the initial rate of water absorption. In terms of the saturation coefficient (K_u), it is considered that its value of less than 0,88 ensures the resistance of the product to freeze-thaw cycles (Radonjanin).

3. Experimental part

3.1. Properties of raw material

In order to make samples of brick, raw materials from a clay pit in the area of eastern Slavonia: Grabovac (Kuševac) were used. The raw material was mechanically homogenized, properly „fabricated“ and of sufficient quality in order to achieve an even shrinkage and necessary plasticity. Properties of raw materials are shown in Figure 1 and in Tables 1 and 2. The grain size distribution of raw materials is determined according to ASTM D 422, the liquid limit, the plastic limit and the plasticity index according to BS 1377 and the moisture of samples according to ASTM D 2216.

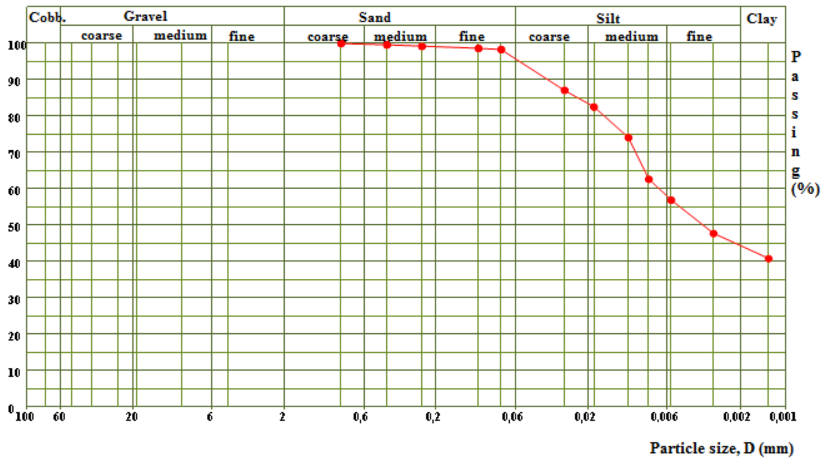

Figure 1 The grain size distribution of raw material (Bušić, 2012.)

Table 1 Test results of particle size distribution (Bušić, 2012.)

Raw material	**Description of particles (form, solidity)**	**Grain (mm)**	C_u	C_c	**G(%)**	**S(%)**	**M(%)**	**C(%)**
Grabovac (Kuševac) - D	round, solid and durable	0,85	-	-	0,00	4,27	51,38	44,35

Abbreviations in the Table: C_u – coefficient of uniformity, C_c – coefficient of curvature, G – gravel, S – sand, M – mould powder, C – clay.

Table 2 Liquid limit, plasticity limit, plasticity index and moisture of raw material (Bušić, 2012)

Raw materials	**Sample description**		**Liquid limit (%)**	**Plasticity limit (%)**	**Plasticity index (%)**	**Moisture (%)**
	Sample preparation	**Passing through the sieve 0,425**				
Grabovac (Kuševac) - D	naturally humid	100 %	57,33	16,02	41,31	36,6

3.3. Brick manufacturing

Samples of bricks with measurements of 12,5/6/3 cm are prepared by machine and by hands, then rolled in sand in order to prevent a rapid moisture loss from the raw material. Samples have been dried during the period of circ. 45 days on a flat surface which was sand-coated and was lying on the floor of a room due to a lower air flow and in order to be protected from a rapid loss of moisture and the too bright sun. During the drying process, shrinkage has been monitored on brick samples and a higher level of shrinkage was noticed on final products that were hand-made bricks in comparison to machine-made bricks. On machine-made bricks, a higher level of shrinkage during the drying process in the direction of brick extrusion through the mould in the production process has been noticed as compared to the direction perpendicular to the direction of brick extrusion. This impact of the direction in the brick production process on the level of its shrinkage during the drying process has not been noticed on handmade bricks. After the drying, samples of bricks were fired in an electric kiln with an increase in temperature of 45 °C/h until reaching a target temperature (1000 °C or 1050 °C) and after reaching it they were kept at the same temperature during a period of 30 min. Shrinkage of bricks has been monitored after the firing process and it has been noticed that a higher firing temeperature causes higher shrinkage of samples on machine-made and handmade bricks. Then again, on machine-made bricks a higher level of shrinkage during the firing process in the direction of brick extrusion through the mould in the production process has been noticed as compared to the direction perpendicular to the direction of brick extrusion. This impact of the direction in the brick production process on the level of its shrinkage during the firing process has not been noticed on handmade bricks.

Figures 2 to 7 show the process of manufacturing brick samples. Regarding the two ways of manufacturing bricks and two different firing temperatures, 4 types/series of bricks were produced.

Figure 2 Machine-made brick

Figure 3 Mould for handmade bricks

Figure 4 Sand-coating of newly made bricks

Figure 5 Bricks after the firing process

Figure 6 Machine-made bricks

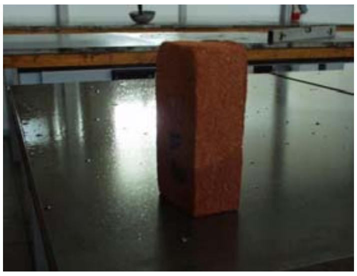

Figure 7 Handmade brick

3.3. Testing of brick properties

Brick properties are tested in accordance with a variety of standards HRN EN 722, and they refer to determining measurements, net and gross density, absorption and initial absorption, compressive strength. The saturation coefficient was determined for each series of bricks as well. The testing of all properties has been carried out on 10 samples from each series of bricks, except determining the saturation coefficient, which has been carried out on 5 samples from each series of bricks.

3.4. Test results and analysis of results

The results of testing the durability properties of bricks are shown by Figures 8 to 13, with average results in all measured values per individual property.

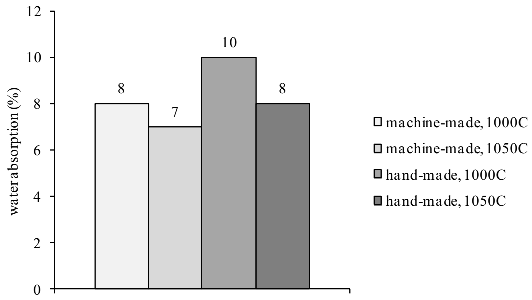

Figure 8 Results of water absorption testing

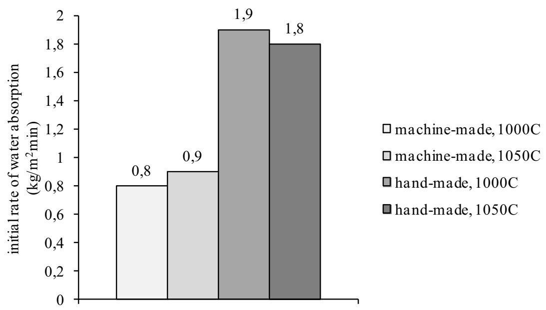

Figure 9 Results of initial rate of water absorption testing

It can be seen from Figure 8 that a handmade brick has higher levels of water absorption and clearly noticeable initial rate of water absorption unlike machine-made bricks (Figure 9). Such results indicate a higher proportion of pores on handmade bricks in comparison to machine-made bricks, which confirms higher values of gross and net dry density in machine-made bricks (Figure 10 and 11). Regarding higher levels of water absorption in handmade bricks, it is assumed that pores of larger diameters have been formed during that type of brick production process. Higher initial rate of water absorption in handmade bricks indicates that pores of smaller diameters are formed, which is opposite to the above mentioned. In both ways of manufacturing bricks, water absorption and initial rate of water absorption have slightly higher values at brick firing temperatures of 1000 °C in comparison to brick firing temperature of 1050 °C. The assumption is that at lower firing temperatures larger pores develop that are then filled with water and tend to lose water quickly which is favourable for the resistance of bricks to frost-thaw cycles and there are indications here that these large pores have been developed in handmade bricks at lower temperatures, which then suggests a longer durability of these bricks.

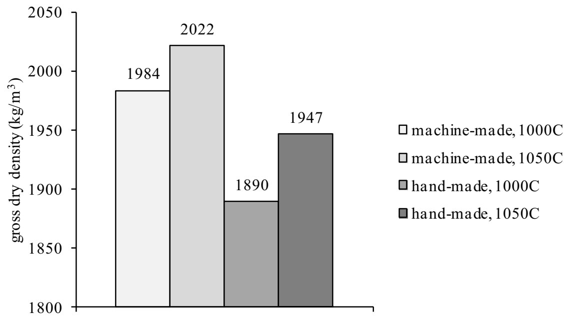

Figure 10 Results of gross dry density testing

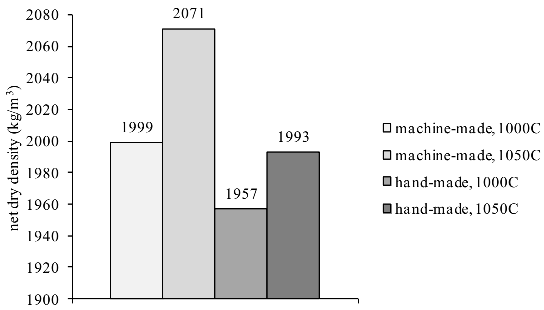

Figure 11 Results of net dry density testing

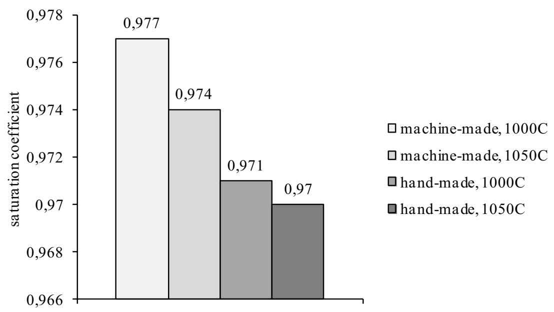

Figure 12 Results of saturation coefficient testing

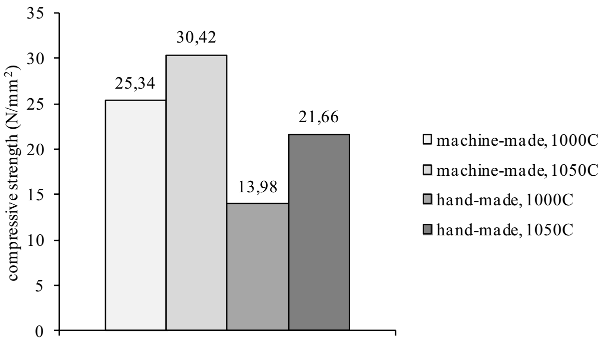

Figure 13 Results of compressive strength testing

In the saturation coefficient (Figure 12) no rules for behaviour in relation to the firing temperature and the type of brick production process have been noticed, but values considerably above the limit which ensures the resistance of bricks to frost -thaw cycles have been observed. Furthermore, compressive strengths (Figure 13) are higher in machine-made bricks than in handmade bricks and generally higher at bricks fired at higher temperatures.

Taking into account that results according to all here observed properties indicate different conclusions, the final conclusion about the resistance of brick to frost-thaw cycles regarding the type of the manufacturing process and firing temperature will be possible to reach after the testing of resistance of bricks to frost-thaw cycles and after having insight into the proportion of pores of certain size in the total pore system.

4. Conclusion

The goal of this research paper is to find out the optimum ways of making and firing temperature of bricks that will result in bricks of sufficient durability intended for use in historic buildings. Given the fact that the results of the investigation presented in this paper do not unambiguously point out the optimum way of manufacturing and firing brick with the aim of reaching her sufficient durability, the final conclusion on the resistance of brick to freeze-thaw cycles with regard to the ways of its production process and firing temperature will be possible to reach after the testing of resistance of bricks to freeze-thaw cycles and after having insight into the proportion of pores of certain size in the total pore system.

Acknowledgments
The authors would like to thank for the funds for the project *"Development of investigation and analysis techniques for the assessment and lifetime expectancy of historical structures",* financed from the pre-accession fund Hungary-Croatia IPA Cross-border Co-operation Programme 2007 – 2013.

LITERATURE

Boynton, R.S., Gutschick, K.A.: Durability of mortar and masonry - Masonry mortar technical notes (1989), Arlington: National Lime Association

Bušić, R.: Influence of production method and firing temperature on properties of clay brick – final paper (2012), Osijek: Faculty of Civil Engineering

HRN EN 771-1:2011 Specification for masonry units -- Part 1: Clay masonry units

HRN EN 772-11:2011 Methods of test for masonry units -- Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units

HRN EN 772-13:2003 Methods of test for masonry units -- Part 13: Determination of net and gross dry density of masonry units

HRN EN 772-16:2011 Methods of test for masonry units -- Part 16: Determination of dimensions

HRN EN 772-3:2003 Methods of test for masonry units - Part 3: Determination of net volume and percentage of voids of clay masonry units by hydrostatic weighing

HRN EN 772-7:2003 Methods of test for masonry units - Part 7: Determination of water absorption of clay masonry damp proof course units by boiling in water

Ikeda, K., Kim, H-S., Kaizu, K., Higashi, A.: Influence of firing temperature on frost resistance of roofing tiles, Journal of the European Ceramic Society; Vol. 24 (2004), pp. 3671-3677

Kung, J.H.: Frost Durability of Canadian Clay Bricks (1985), Ottawa: National Research Council Canada

Larsen, P.K.: Moisture physical properties of bricks-Technical report (1995), Holzkirchen: Technical University of Denmark

Radić, J.: Trajnost konstrukcija 1 (2010), Zagreb: Jadring Radonjanin, V., Malešev, M.: Notes in lectures