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Influence of Technological Factors on the Physical-Mechanical Properties of Clay Masonry Units

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In this work the influence of eight technological factors (clay, non-plastic materials, burning out additive, waste materials, mixing effectiveness in a mixer, degree of compression in formation heads, level of vacuuming in a vacuum chamber, duration of keeping at the highest burning temperature) on the determined physical-mechanical properties of ceramic samples: compressive strength, bending strength, water absorption, net dry density, gross dry density, is analysed applying fractional factorial design at two levels. Linear regression equations are derived enabling to predict the values of physical-mechanical properties of clay masonry units or knowing the desirable values of the properties to determine the optimal effect of the technological factors under investigation and thus to produce the clay masonry units of different purpose with the desirable properties within certain limits.

Keywords: clay masonry units, experimental design, compressive strength, bending strength, water absorption, net and gross dry density.

INTRODUCTION

The clay masonry units' production process includes many technological operations, each of them influences the final product quality. To analyse the influence of all technological factors on the product properties and the reciprocity is a complicated, expensive and labour-intensive operation. For that purpose special statistical methods and means may be applied enabling to analyse the reciprocity of technological factors and the influence on qualitative characteristics of products quite clear and objectively, to find their optimal values decreasing the number of experiments considerably [1, 2].

There is a fair amount of works, where the experimental design was applied for determination of technological factors` influence on product quality [3 – 8]. Advantage of this method over the classical analysis methods is the decrease in a number of experiments and a big amount of statistically proved information from the analysis of investigation results enabling to make the concrete conclusions.

The influence of technological factors on the quality of clay masonry units in our country was analysed in [5 – 7]. These technological factors were examined: level of vacuuming in a vacuum chamber, length of pressure and formation heads, speed of formation band outlet from a formation head, treatment and composition of formation mix, drying and burning regimes of semimanufacturer and organic film applied. Many of works investigating the influence of technological factors on the frost resistance of clay masonry units were performed by A. Sadūnas [8]. J. Malaiškienė and R. Mačiulaitis [9] have analysed in details the interdependence of separate components of formation mix and various structural parameters of ceramic body. Their work is special as the regression analysis of two stages has been performed for the first time. It allowed determining not only the reliable empirical dependence of the separate components of material mix on the main structural characteristics of ceramic body, but also vice versa, the dependence of each structural parameter on the formation mix components. It all creates new possibilities for regulation of technological production process and increases the reliability of forecasting. The authors [6, 7] who analysed more technological factors that have an effect on the characteristics of ceramic articles established that besides the influence of formation mix's composition, manufacturing factors also influence the characteristics of the articles significantly. Therefore, a thorough investigation is needed on the influence of technological factors on the characteristics of ceramic articles.

The aim of this work is to analyse the significance of the selected technological factors, the influence of significant factors on the determined physical-mechanical properties of ceramic samples applying the experimental design and to derive the linear regression equations, enabling to predict the physical-mechanical properties of clay masonry units or knowing the desirable properties to determine the optimal values of the technological factors under investigation.

MATERIALS AND INVESTIGATION METHODS

For formation of samples these materials from Lithuanian mines were used: clay A and the thinner clay B, sand, crushed brick, burning out additive – anthracite, waste materials – glass, catalyst from the catalyst-cracking reactor. The sand was sieved through the 1 mm aperture sieve, the crushed stone was crumbled by alligator and sieved through the 2.5 mm sieve. For the anthracite the sieve with 2 mm apertures was used, the glass was ground in the disintegrator and sieved through the 1 mm apertures, the catalyst was applied in the form of granules

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(1.3 – 1.5 mm). Components of the formation mix were dosed by mass, mixed by the two-roll screw mixer of Z type, moistened to the humidity necessary for formation and left to lie for 4 days. The tiles with dimensions (120×60×40) mm and 14 cavities were formed by the band vacuum press. The tiles were dried in natural conditions. The dried tiles were burned in the electric semi-industrial stove at the highest clay A burning temperature.

Ceramic samples were produced according to the fractional factorial design at two levels. Eight technological factors were selected, changing in two level (Table 1), that are conditionally encoded: –1.0 (conditionally bad) and 1.0 (conditionally good). In the case of full plan the number of experiments allowing to investigate the interaction of all factors would be $N = 2^8 = 256$, and applying the partial plan $2^{(k-p)} = 2^{(8-4)}$ [1, 2], the number of experiments was decreased to 16 tests. According to the developed randomising experiment matrix, 16 batches of ceramic samples were produced and their physical-mechanical properties determined. Compressive strength ($f_{exp.}$) was determined according to LST EN 772-1:2003, bending strength ($R_{exp.}$) – according to LST 1272-92, water absorption ($W_{exp.}$) according to – LST EN 771-1:2003, net dry density ($\rho_{n.u.exp.}$) and gross dry density ($\rho_{g.u.exp.}$) – according to LST EN 772-13.

Results of the experiments were processed by the experimental design software [10].

Table 1. Table of factors` encoding

Notation	Factor	Conditionally bad		Conditionally good	
x_1	Clay (A or A+B)	-1	A (P* = 19.1)	1	A + B (20 % of clay A mass) (P* = 11.14)
x_2	Non-plastic materials (sand + crushed stone)	-1	8 % (5 % sand + 3 % crushed stone)	1	8 % (5 % sand + 3 % crushed stone)
x_3	Burning out additive (anthracite)	-1	0 %	1	1.2 %
x_4	Waste materials (catalyst + glass)	-1	0 %	1	22.8 % (6 % catalyst + 16.8 % glass)
x_5	Mixing effectiveness	-1	5 min	1	15 min
x_6	Level of vacuuming	-1	0.65 MPa	1	0.9 MPa
x_7	Degree of compression	-1	Short formation head	1	Long formation head
x_8	Burning duration	-1	Keeping at the highest burning temperature for 1 h	1	Keeping at the highest burning temperature for 5 h

* P – average plasticity number.

RESULTS AND ANALYSIS

Performing the analysis of average compressive strength values we have determined that the technological factors: x_1 (clay), x_2 (non-plastic materials), x_3 (burning out additive), x_4 (waste materials) have the significant influence on the compressive strength of ceramic samples, and other factors have insignificant influence. Conditional influence of technological factors effect on compressive strength is presented in Fig. 1. Conditional values of effects are interpreted so: we decide on the magnitude of influence from the numerical value, and we decide on the positive or negative influence of technological factor on the property under investigation from the sign. Statistical significance $p = 0.05$ shows the possibility of error, i.e. the possibility to fall into error 5 %.

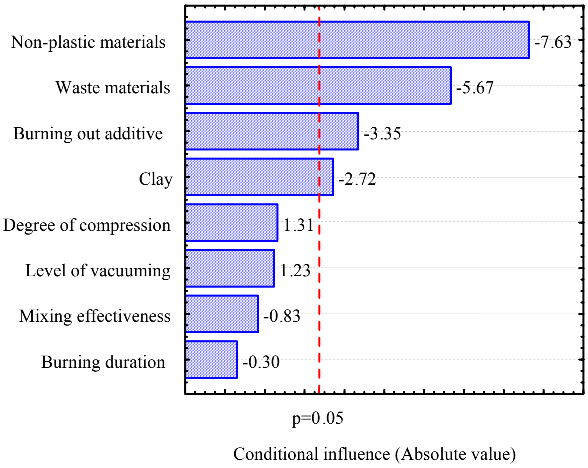

Fig. 1. Conditional influence of technological factors on average compressive strength

The coefficients of linear regression model equation (equation 1) together with the standard error and the reliability intervals –95 % and +95 % are presented in Table 2.

$$A = b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5+b_6x_6+b_7x_7+b_8x_8 \quad , \qquad (1)$$

(where A is the property, b_0 is the overall average coefficient, b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8 are the coefficients of the first set effects, x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8 are the correspondingly the equation of technological factor (–1 or 1)).

Table 2. Coefficients of linear regression equation for compressive strength

Factor	Regression coefficient, b_i	Standard error	–95, %	+95, %
Overall average coefficient	34.37	0.66	32.81	35.93
Clay (x_1)	–2.81	1.03	–5.25	–0.36
Non-plastic materials (x_2)	–6.20	0.81	–8.12	–4.28
Burning out additive (x_3)	–2.98	0.89	–5.08	–0.87
Waste materials (x_4)	–5.83	1.03	–8.27	–3.40
Mixing effectiveness (x_5)	–0.64	0.77	–2.47	1.19
Level of vacuuming (x_6)	0.87	0.71	–0.80	2.55
Degree of compression (x_7)	1.12	0.85	–0.89	3.13
Burning duration (x_8)	–0.40	1.32	–3.53	2.74

Writing the obtained values of regression coefficients to the equation 1 we have derived the linear regression model equation for compressive strength:

$$f_{calc.} = 34.37 - 2.81x_1 - 6.20x_2 - 2.98x_3 - 5.83x_4 - - 0.64x_5 + 0.87x_6 + 1.12x_7 - 0.40x_8 \ , \qquad (2)$$

As the significant effects are made only by factors x_1, x_2, x_3, x_4, excluding the influence of insignificant factors, the simplified regression equation is obtained:

$$f_{calc.} = 34.37 - 2.67x_1 - 5.82x_2 - 2.22x_3 - 5.35x_4 \ , \qquad (3)$$

Comparing the adequacy of experimental and calculated data according to Fisher criteria when the significance level is $\alpha = 5$ %, we confirm that equations of models are adequate.

Diagrams of significant technological factors dependencies are presented in Fig. 2 and Fig. 3.

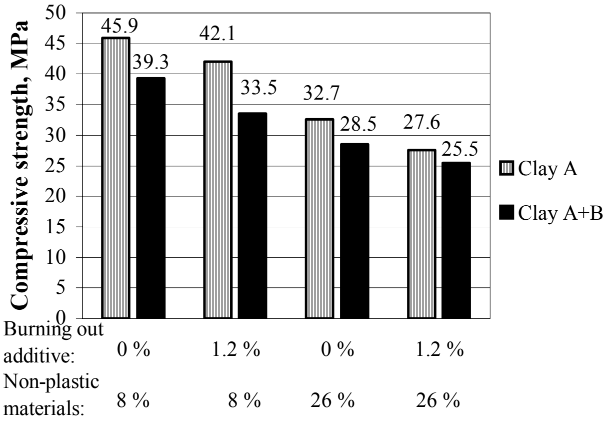

Fig. 2. Dependence of compressive strength on quantity of clay, non-plastic materials and burning out additive

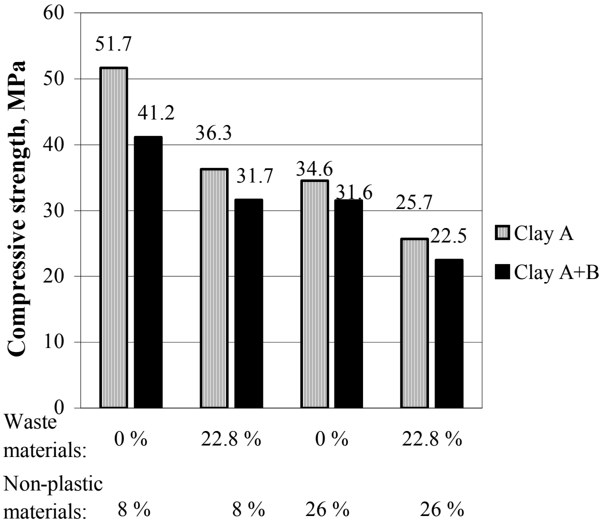

Fig. 3. Dependence of compressive strength on quantity of clay, non-plastic materials and waste materials

Analogously the analysis of average values of bending strength, water absorption, net dry density and gross dry density was performed. Conditional influence of technological factors effects is presented correspondingly in Figures 4, 6, 8 and 10. Coefficients of linear regression model equation together with the standard error and the reliability intervals –95 % and +95 % are presented in Tables 3, 4, 5 and 6. Diagrams of significant technological factors influences are presented in Figures 5, 7, 9, 11, 12 and 13.

The linear regression model equations are obtained for: bending strength (equation 4), water absorption (equation 5), net dry density (equation 6), gross dry density (equation 7):

$$R_{calc.} = 5.66 + 0.68x_1 + 0.005x_2 - 0.15x_3 + 0.17x_4 + + 0.30x_5 + 0.21x_6 + 0.15x_7 + 0.89x_8 \ , \qquad (4)$$

$$W_{calc.} = 5.94 - 0.74x_1 + 0.29x_2 + 0.22x_3 + 1.03x_4 - - 0.57x_5 + 0.08x_6 + 0.71x_7 - 2.12x_8 \, , \qquad (5)$$

$$\rho_{n.u.\ calc.} = 2043.12 + 31.65x_1 - 13.40x_2 - 24.24x_3 - - 30.80x_4 + 29.98x_5 + 13.35x_6 - 28.51x_7 + 85.39x_8 \, ,(6)$$

$$\rho_{g.u.\ calc.} = 1815.62 + 47.37x_1 + 12.40x_2 - 10.83x_3 - - 9.85x_4 + 33.51x_5 + 1.43x_6 - 1.05x_7 + 76.03x_8 \, , \qquad (7)$$

Excluding the influence of insignificant factors these simplified linear regression equations are obtained for: bending strength when $p = 0.055$ (equation 8), water absorption when $p = 0.07$ (equation 9), net dry density when $p = 0.07$ (equation 10), gross dry density when $p = 0.05$ (equation 11):

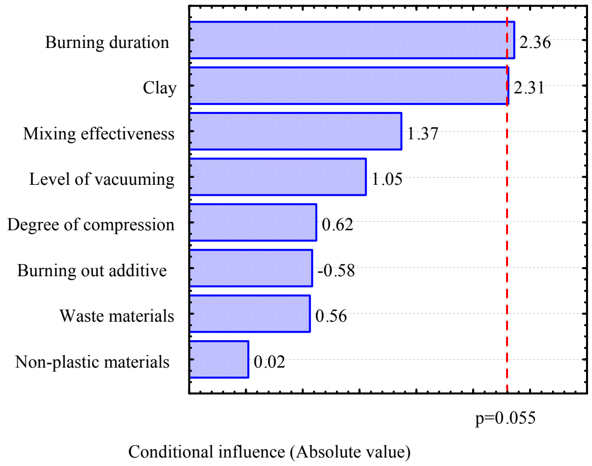

Fig. 4. Conditional influence of technological factors on average bending strength

Table 3. Coefficients of linear regression equation for bending strength

Factor	Regression coefficient, b_i	Standard error	–95, %	+95, %
Overall average coefficient	5.66	0.19	5.21	6.10
Clay (x_1)	0.68	0.29	–0.02	1.38
Non-plastic materials (x_2)	0.005	0.23	–0.54	0.55
Burning out additive (x_3)	–0.15	0.25	–0.75	0.45
Waste materials (x_4)	0.17	0.29	–0.53	0.86
Mixing effectiveness (x_5)	0.30	0.22	–0.22	0.82
Level of vacuuming (x_6)	0.21	0.20	–0.26	0.69
Degree of compression (x_7)	0.15	0.24	–0.42	0.72
Burning duration (x_8)	0.89	0.38	–0.0015	1.79

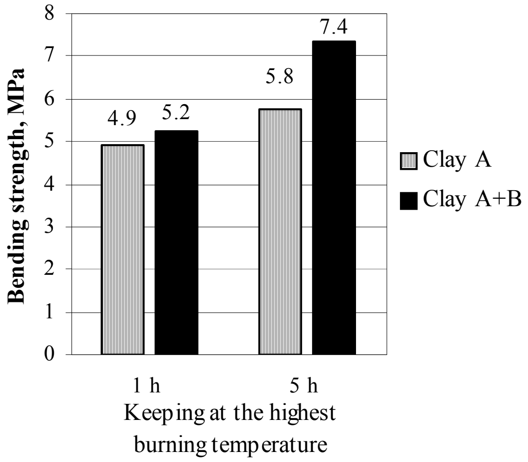

Fig. 5. Dependence of bending strength on clay and duration of keeping at the highest burning temperature

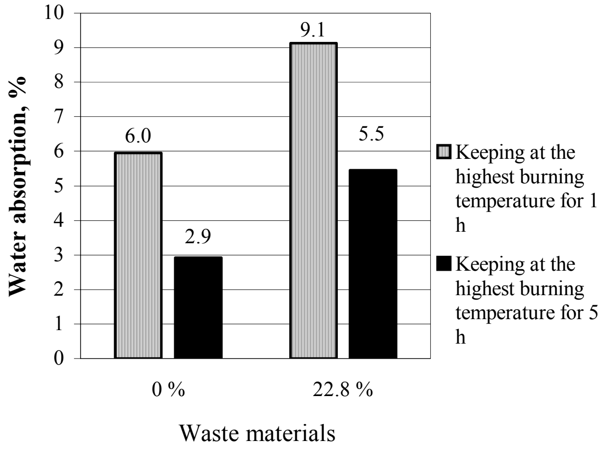

Fig. 7. Dependence of water absorption on the quantity of waste materials and duration of keeping at the highest burning temperature

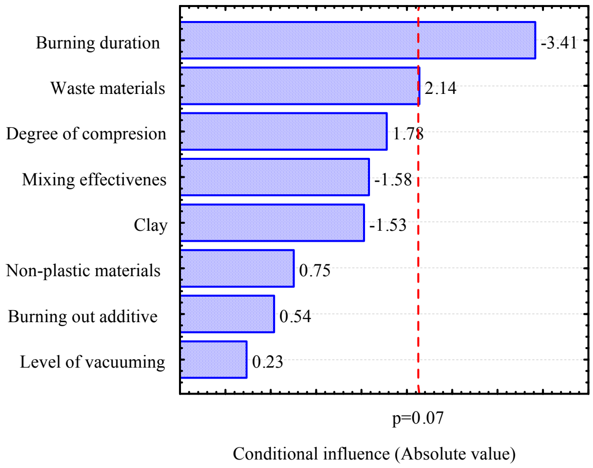

Fig. 6. Conditional influence of technological factors on average water absorption

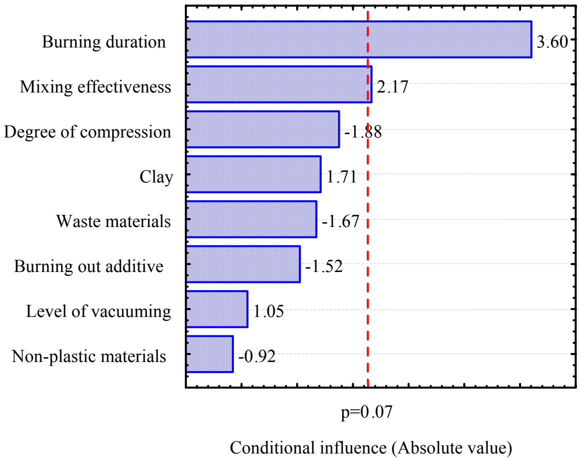

Fig. 8. Conditional influence of technological factors on average net dry density

Table 4. Coefficients of linear regression equation for water absorption

Factor	Regression coefficient, b_i	Standard error	–95, %	+95, %
Overall average coefficient	5.94	0.31	5.21	6.67
Clay (x_1)	–0.74	0.48	–1.87	0.40
Non-plastic materials (x_2)	0.29	0.38	–0.61	1.19
Burning out additive (x_3)	0.22	0.42	–0.76	1.21
Waste materials (x_4)	1.03	0.48	–0.11	2.17
Mixing effectiveness (x_5)	–0.57	0.36	–1.43	0.28
Level of vacuuming (x_6)	0.08	0.33	–0.71	0.86
Degree of compression (x_7)	0.71	0.40	–0.23	1.65
Burning duration (x_8)	–2.12	0.62	–3.59	–0.65

Table 5. Coefficients of linear regression equation for net dry density

Factor	Regression coefficient, b_i	Standard error	–95, %	+95, %
Overall average coefficient	2043.12	11.78	2015.27	2070.98
Clay (x_1)	31.65	18.49	–12.08	75.38
Non-plastic materials (x_2)	–13.40	14.52	–47.74	20.94
Burning out additive (x_3)	–24.24	15.90	–61.84	13.36
Waste materials (x_4)	–30.80	18.41	–74.33	12.73
Mixing effectiveness (x_5)	29.98	13.82	–2.71	62.66
Level of vacuuming (x_6)	13.35	12.68	–16.63	43.33
Degree of compression (x_7)	–28.51	15.20	–64.45	7.43
Burning duration (x_8)	85.39	23.70	29.34	141.44

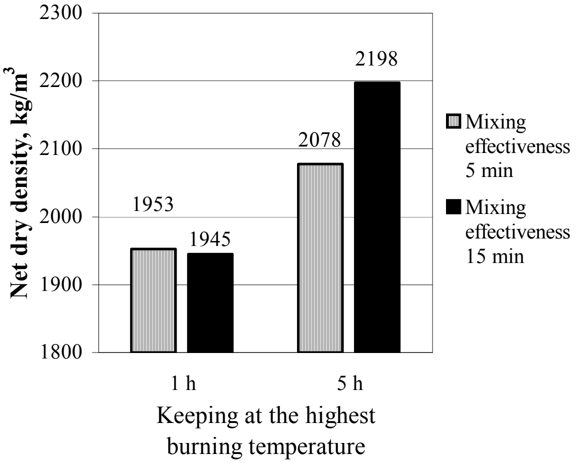

Fig. 9. Dependence of net dry density on mixing effectiveness and duration of keeping at the highest burning temperature

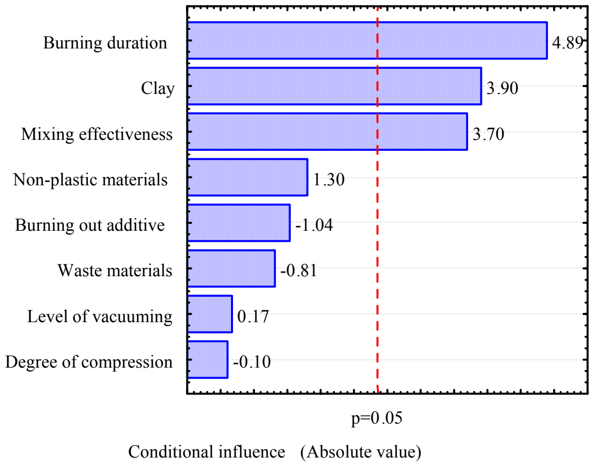

Fig. 10. Conditional influence of technological factors on average gross dry density

Table 6. Coefficients of linear regression equation for gross dry density

Factor	Regression coefficient, b_i	Standard error	–95, %	+95, %
Overall average coefficient	1815.62	7.72	1797.36	1833.89
Clay (x_1)	47.37	12.13	18.69	76.06
Non-plastic materials (x_2)	12.40	9.52	–10.13	34.92
Burning out additive (x_3)	–10.83	10.43	–35.50	13.83
Waste materials (x_4)	–9.85	12.07	–38.40	18.70
Mixing effectiveness (x_5)	33.51	9.07	12.07	54.95
Level of vacuuming (x_6)	1.43	8.32	–18.24	21.09
Degree of compression (x_7)	–1.05	9.97	–24.62	22.52
Burning duration (x_8)	76.03	15.55	39.27	112.79

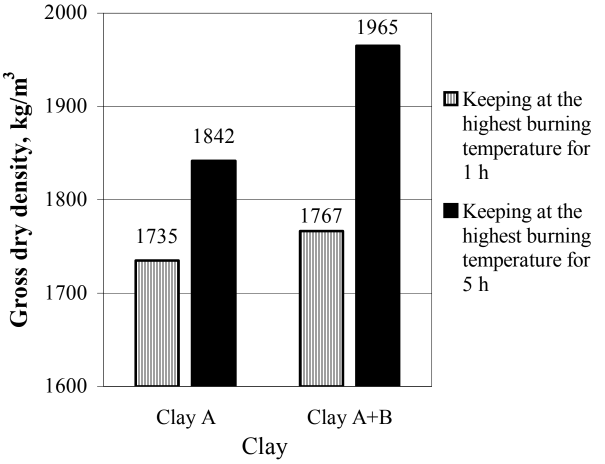

Fig. 11. Dependence of gross dry density on clay and duration of keeping at the highest burning temperature

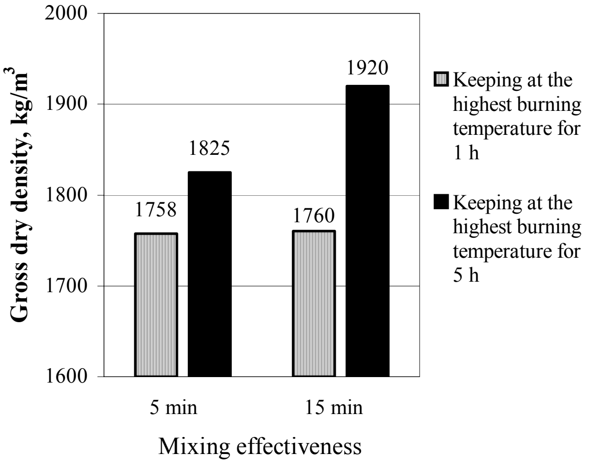

Fig. 12. Dependence of gross dry density on mixing effectiveness and duration of keeping at the highest burning temperature

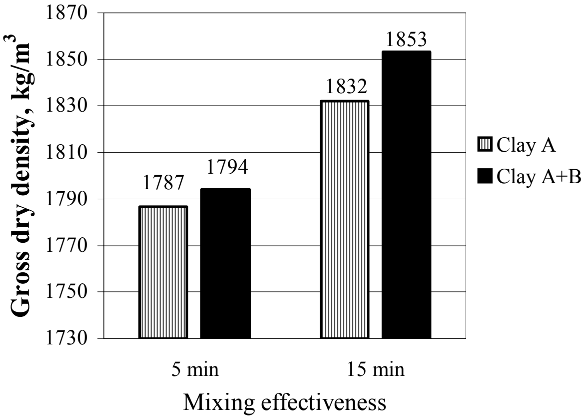

Fig. 13. Dependence of gross dry density on mixing effectiveness and clay

$$R_{calc.} = 5.66 + 0.48x_1 + 0.75x_8 \ , \tag{8}$$

$$W_{calc.} = 5.94 + 1.43x_4 - 1.68x_8 \ , \tag{9}$$

$$\rho_{n.u.\ calc.} = 2043.12 + 28.13x_5 + 94.37x_8 \ , \tag{10}$$

$$\rho_{g.u.\ calc.} = 1815.62 + 51.14x_1 + 37.16x_5 + 72.44x_8 \ , \tag{11}$$

Knowing the effectiveness of technological factors influence on the physical-mechanical properties and the regression model equations we can model the production conditions for the determined properties of clay masonry units. For example, if we want to produce an item with the biggest compressive strength, at first we select the qualitative factors having positive influence on the mentioned property, in this case we select clay A. We insert the quantitative factors, expressed by natural magnitudes, to the simplified regression model equation for compressive strength (3) and we obtain:

$$f_{calc.} = 55.60 - 0.65X_2 - 3.70X_3 - 0.47X_4 \;, \qquad (11)$$

where X_2 is the amount of non-plastic materials, %; X_3 is the amount of burning out additives, %; X_4 is the amount of waste materials, %.

Analogous operations are made with the regression model equations for other properties as well. Regression model equations for bending strength, water absorption, net dry density and gross dry density are obtained:

$$R_{calc.} = 4.06 + 0.38X_8 \;, \qquad (12)$$

$$W_{calc.} = 7.03 + 0.13X_4 - 0.84X_8 \;, \qquad (13)$$

$$\rho_{n.u.\ calc.} = 1845.31 + 5.63X_5 + 47.19X_8 \;, \qquad (14)$$

$$\rho_{g.u.\ calc.} = 1581.50 + 7.43X_5 + 36.22X_8 \;, \qquad (15)$$

where X_4 is the amount of waste materials, %; X_5 is the mixing effectiveness, min; X_8 is the duration of keeping at the highest burning temperature, h.

According to these equations the values of physical-mechanical properties of clay masonry units may be predicted. For example, applying the clay A with 8 % of non-plastic materials, without waste materials and burning-out additives, mixing for 15 minutes and keeping at the highest burning temperature for 1 h we obtain that $f_{calc.} = 50.4$ MPa, $R_{calc.} = 4.4$ MPa, $W_{calc.} = 7.2$ %, $\rho_{n.u.calc.} = 1977$ kg/m^3 and $\rho_{g.u.calc.} = 1729$ kg/m^3.

Determining the necessary values of physical-mechanical properties and evaluating the possible variation limits and solving the system of equations (11 – 15) we can obtain the optimal values of technological factors.

CONCLUSION

Modelling the production conditions according to the derived linear regression model equations we can predict the values of physical-mechanical properties of clay masonry units. Determining the necessary values we can solve the reciprocal problem, i.e. to find the optimal values of technological factors.

We have determined that the quantity of formation mix components has the biggest influence on compressive strength of ceramic samples. Increasing the amount of non-plastic materials from 8 % to 26 %, amount of waste materials from 0 % to 22.8 %, amount of burning out additives from 0 % to 1.2 %, the compressive strength of ceramic samples decreases.

Increasing the amount of waste materials from 0 % to 22.8 % the water absorption increases.

The additive of the thinner clay B increases the bending strength and the gross dry density.

Prolonging the duration of keeping at the highest burning temperature from 1 h to 5 h the bending strength of ceramic samples increase, this may be explained by the change in ceramic body fragility as the glass phase expands, also the net dry density and the gross dry density increase, the water absorption decreases.

Increasing the duration of mixing from 5 min to 15 min the net dry density and the gross dry density increase.

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