Construction and Building Materials 110 (2016) 8–16

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The influence of mullite wool waste on the properties of concrete and ceramics

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HIGHLIGHTS

- Utilizing of mullite wool waste.
- Effect on the structure.
- Strength characteristics.

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 1 February 2016
Accepted 2 February 2016
Available online 9 February 2016

Keywords:
Cement concrete
Ceramics
Mullite wool waste
Waste processing
Properties
Durability

ABSTRACT

The influence of technogenic waste (burned and unburned mullite wool) on the properties of cement concrete as well as the influence of unburned mullite wool on the properties of ceramics are analysed in the paper. For the purpose of research, the part of sand in a cement concrete (2%, 4%, 6%, 8%, 10%) was replaced by a mullite wool waste. When 10% of the burned mullite wool waste was used the compressive strength of concrete increased by 7.7% after 7 days, and by 3.2% after 28 days. When 8% of the unburned mullite wool waste was used the compressive strength of concrete decreased by 3.4% after 7 days, and by 12.2% after 28 days. The ceramic samples were made from 4 different formation mixtures, in which the amount of unburned mullite wool waste was 0%, 5%, 10% and 15% (the amounts of quartz sand were replaced with waste). The samples were burned at the temperatures of 1050 °C and 1080 °C, keeping them at these temperatures for 4 h. The experimental results showed that the application of mullite wool waste in the manufacture of ceramic products is beneficial because of its positive impact on ceramic properties and the possibility to avoid overloading landfill sites. At the optimum burning temperature of 1080 °C, the significantly higher frost resistance, compressive strength and lower water absorption of ceramics is obtained.

1. Introduction

The mullite wool waste forms during the production of thermal insulation material. This thermal insulation material is used in industrial thermal equipment, for example, in the manufacture of electric and gas stoves, gas furnaces. It might also be applied for insulation works in boiler rooms or for insulation of different boilers, reactors, turbines, generators or cable lines, passing closely to the heat sources. In the foundry industry, these thermal insulation panels are used for futeration of buckets or to seal the apertures of casting machines. They are also used to build fire screens. The panels must have precise dimensions. The sawing and grinding of the panels lead to large amounts of waste. The waste forms during two stages of production: before burning and after burning.

Our previous research [1] presented the analysis of the influence of burned mullite wool waste on the properties of ceramics. It showed the most rapid water absorption and settlement in the ceramic samples without waste additive, while slower water absorption was noticed for the samples with 10% of waste additive. However, after three days the values of water absorption were almost equal. The estimated average frost resistance (when samples were burned at the temperature of 1080 °C) varied from 220 cycles (for the samples without waste additive) to 440 cycles (for the samples with 10% of mullite wool waste). The mullite wool waste is decreasing the density of a ceramic body, its structural inhomogeneity and the rate of capillary absorption and it increases significantly the compressive strength. Taking into account frost resistance and compressive strength, the optimum quantity of the waste in a formation mixture is 10%, when the samples are

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.011
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burned at the temperature of 1080 °C [1]. In the other study [2] it was determined, that the optimum quantity of the waste in the production of frost resistant ceramics under the maximum burning temperature of 1050 °C is 5%. To obtain stronger ceramic products, 15% of the burned mullite wool waste should be added. In that case the compressive strength would be 23 MPa. However, the estimated frost resistance of such ceramic body would be only 65 cycles.

The unburned mullite wool waste was used only in the research of expanded clay concrete [2]. The investigations showed that the additive of unburned mullite wool waste decreases frost resistance and density of samples, and increases their water absorption. Replacing 10% of the cement with the unburned mullite wool waste almost does not change the compressive strength. This waste can be used for expanded clay concrete wall blocks and masonry, protected from the aggressive impact of environment [2].

Mullite ($3Al_2O_3{\cdot}2SiO_2$) and mullite ceramics are widely used in many fields because of their excellent mechanical properties, high melting points (1830 °C), low coefficients of thermal expansion ($4.5 \times 10^{-6}\,K^{-1}$), excellent creep resistance, good chemical stability, and resistance to high temperatures [3–5]. The authors [5] revealed that the content of mullite grows with an increase in the sintering temperature from 1100 °C to 1500 °C. The other researchers [6] state that the density of mullite is $3.2\,g/cm^3$, and the strength about 200 MPa. Alumina-mullite ceramics with a low content of glass phase may have a high potential for armour and wear resistance applications if these ceramics have an optimal ratio between two major crystalline phases and, therefore, a remarkable level of physical properties [7]. The unburned mullite wool used in our studies was characterized by a relatively large amount of glass phase.

The authors [8] examined different methods of synthesizing mullite from clay. They determined that in case the Algerian kaolinite was used the mullite formed at 1550 °C. In the studies of ceramics often the additives with higher amounts of Al_2O_3 and SiO_2 are used in order to obtain mullite. The researchers [9] examined ceramics made with foam-gelcasting, using $CaCO_3$, SiO_2, Al_2O_3-ά. They determined that the produced mullite highly influences the microstructure and properties of ceramics. The compressive strength changed from 4.2 to 30.9 MPa. Other researches [10,11] used fly ash. The authors [10] discovered that when ceramics comprising mullite, sillimanite and quartz is burned at 1200 °C the mullite, cristobalite and ά-Al_2O_3 form. However, when the temperature is increased to 1400 °C and kept constant for 2 h, only mullite is obtained. In addition, the other authors [11] also state that only mullite is produced when ceramic samples are burned at the temperature of 1400 °C.

The studies of ceramics often include the analysis of technogenic raw material (catalyst) of oil industry, which is rich in Al_2O_3 (68.85–85.25%). Such studies were also performed by the scientists [12,13]. They burned the ceramic samples with this waste and determined that mullite already forms at the temperature of 1100 °C.

A number of different wastes are used for concrete mixtures: crushed ceramic bricks [14–16], plastic waste [17], crushed glass [18], waste from mines [19] etc.

The authors [20] state that carbon fibres might be classified into three groups: long 1.5–2.6 mm, average 0.25–1.5 mm and fine 38 μ–0.25 mm. The fibres distribute unevenly in the sample of porous concrete. Adding carbon fibre to the aerated concrete mixture, the V/K ratio has to be increased. However, the fluidity of a formation mixture still decreases in proportion to the fibre amount. Adding more than 0.4% of the fibre makes the samples almost impossible to form as the formation mixture is fluid and the fibres cannot be distributed evenly in a formation mixture. The fibres increase significantly the strength of porous concrete. A small amount of this additive (0.05%) makes the porous concrete stronger even by 13.6%. Increasing the amount of this additive up to 0.2%, the compressive strength increases 1.45 times. This is explained by the arrangement of newly formed derivatives in the hollows of fibres and the even distribution of fibres in the structure of porous concrete.

Sinica [21] analysed porous concrete with synthetic fibre (length of fibres 5.2 mm, diameter 4.6–7.7 μm) and glass fibre (length of fibres 5 mm) additives. He determined that the cohesion of non-autoclaved foamed cement concrete with fibres is smaller than the fibre tearing force. When tension or bending forces are applied to cement concrete, the fibres loosen as the reinforcement material fibre itself is stronger than the cohesion between fibre and cement concrete. The reinforcement fibres change slightly the compression strength of a composite. The 0.4% additive of synthetic fibres increase the bending strength of a composite by 50%, the 0.4% additive of glass fibres increase the bending strength by 70% compared to the bending strength of a control sample.

The researchers [22,23] analysed the influence of fibre additives on the properties of autoclaved aerated concrete. The following 5 mm fibre reinforcement additives were used: (diameter 6.15 μm), polypropylene (diameter 7.5 μm), basalt wool (diameter 4.6 μm), and kaolin wool (diameter 3.3 μm). It was defined that the mineral fibres (basalt and kaolin) react chemically with the binding material and adhere very well. The 0.3% of hydrophilised fibres increased the compressive strength by 45.5%, while 0.2% of it increased the bending strength by 35.6%.

The aim of this study is to determine the influence of mullite wool waste on the properties of ceramics and concrete.

2. Raw materials and investigation methods

The following raw materials were used for concrete: composite limestone Portland cement CEM II/A-L 42.5N, conforming standard EN 197-1 requirements (its chemical and mineralogical composition is presented in Tables 1 and 2, other properties in Table 3); natural sand, conforming to standard EN 12620, with the maximum size of particles equal to 4 mm (the properties are given in Table 4, the graph of granulometric composition in Fig. 1); gravel, conforming to standard EN 12620, of 4/16 fraction (the characteristics are provided in Tables 5 and 6, the graph of granulometric composition in Fig. 2). The obtained gravel impact resistance to crushing was SZ = 24.9%, resistance to wear 13.0%.

Concrete mixtures also included superplasticiser and waste (burned and unburned mullite wool).

The used superplasticiser MC-PowerFlow 3100 conforms to the requirement of standard EN 934-2. “MC-PowerFlow” is manufactured on the basis of the newest polycarboxylate ether technology. Due to the accelerated adsorption, the effect starts immediately. The manufacturer declares that this superplasticiser is especially suitable for the manufacture of stable, non-exfoliating concrete. The used water conforms to the requirements of standard EN 1008.

The chemical composition of the mullite wool waste is presented in Table 7; the X-ray picture of the unburned mullite wool waste is shown in Fig. 3, and the one of the burned mullite wool – Fig. 4.

The X-ray of the burned mullite wool waste shown in Fig. 3 indicates, that the main mineral in the wool is M mullite $3Al_2O_3$

Table 1
Chemical composition of Portland cement.

Chemical composition, %						
SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3^{2-}	Other
20.61	63.42	5.45	3.36	3.84	0.80	2.52

Table 2
Mineralogical composition of Portland cement.

Mineralogical composition, %				
C_3S	C_2S	C_3A	C_4AF	Other
57.26	15.41	8.68	10.15	8.50

Table 3
Cement strength characteristics and binding times.

Cement properties	CEM II/A-L 42.5 N
Compressive strength, MPa	
After 2 days	21 ± 3
After 28 days	47 ± 3
Initial setting time, min	190
Amount of water for normal consistency, %	25.1
Specific surface area, cm^2/g	3800
Bulk density, kg/m^3	1100
Specific gravity, kg/m^3	3200

Table 4
Physical characteristics of sand 0/4.

Fraction	Characteristics			
	Particle density, kg/m^3	Bulk density, kg/m^3	Water absorption, %	Amount of fine particles < 0.063 mm, %
0/4	2650	1670	0.59	0.63

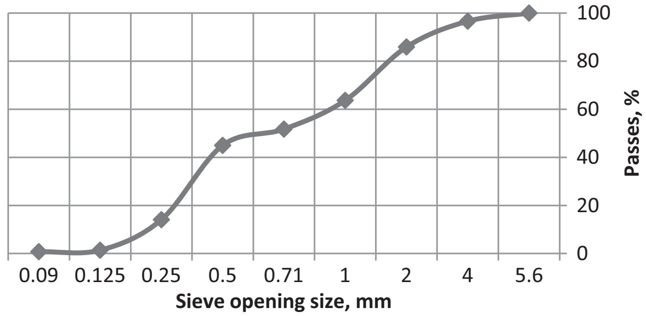


Fig. 1. Granulometric composition of sand.

Table 5
Physical mechanical properties of gravel 4/16.

Characteristic	Test results
Particle density, kg/m^3	2670
Bulk density, kg/m^3	1597
Water absorption, %	1.30
Cleavage, %	19
Amount of fine particles < 0.063 mm, %	0.37

$2SiO_2$ (0.540, 0.340, 0.288, 0.270, 0.254, 0.243, 0.229, 0.220, 0.213, 0.184, 0.170, 0.160, 0.152, 0.147, 0.144) nm, also amorphous SiO_2 (0.426) nm. As seen in Fig. 4, the main mineral of the waste is mullite $3Al_2O_3$ $2SiO_2$ (0.341, 0.256) nm; also there is some amorphous SiO_2 (0.400) nm. Analysing the unburned mullite wool waste, it was determined that the active SiO_2 constitutes 50% of the total SiO_2.

The microstructural analysis of the burned and unburned mullite wool waste was performed using microscope Carl Zeis Evo LS 25. The microstructure of the used raw materials is shown in Fig. 5.

Table 6
Frost resistance of gravel 4/16 (test using magnesium sulphate).

Characteristic, unit of measurement, test method	Test results			
	Part of fraction mass, %	Sample number	Measurement value	Average value
Frost resistance – MS, % (LST EN 1367-2: 2010)	100.0	1 2	7.30 7.36	7.33

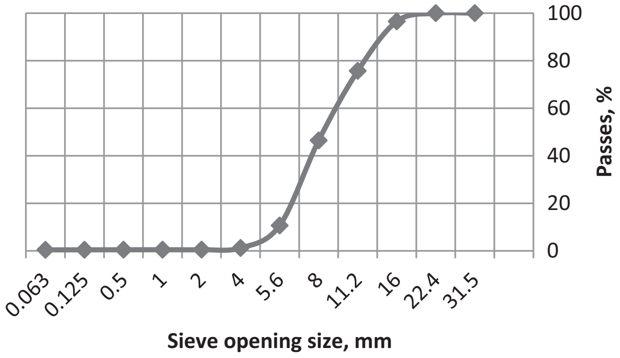


Fig. 2. Granulometric composition of gravel.

Table 7
Average chemical composition of mullite wool waste.

Chemical composition, %	
SiO_2	Al_2O_3
51–52	48–49

Fig. 5 demonstrates that the structure of mullite wool waste changes during burning: thin long fibres break into shorter fragments, the volume of inter fibre space changes (it becomes smaller), parts of fibres partially fuse with each other. The shape of larger insertions in the wool does not change. Both waste groups can be assigned to the group of fibre additives. Due to their structure, fibre additives can improve the strength characteristics of concrete.

To determine the influence of the aforementioned waste material on the physical-mechanical properties of concrete, the samples were formed having the compositions given in Table 8. The amounts of cement and water were changed to keep the constant *W*/*C* ratio and slump class. Mullite wool absorbs water well. Therefore, to keep the constant slump, it was necessary to add water.

The slump of concrete mixture was determined according to the standard EN 12350-2, and the density according to the standard EN 12350-6.

The water and waste suspension was made while preparing the concrete and intensively mixing it by hands. The obtained suspension was placed into a concrete mixer and mixed for 3 min. Previously, the dry materials (cement, fillers) were mixed in a mixer for 1 min. In the preparation of ceramics, all raw materials were initially mixed dry and the certain amounts of water were applied later on. The materials were manually mixed.

The formed samples with dimensions 100 × 100 × 100 mm were left in normal conditions for 1 day. Afterwards, they were held in water of 20 ± 2 °C temperature for 27 days. The concrete samples were made and the hardening (to determine strength) was performed according to standard 12390-2. The compressive strength of concrete samples was determined following the standard EN 12390-3, while the density of hardened concrete according to EN 12390-7. In order to determine flexural strength the samples of prism shape were used. The samples were hardened

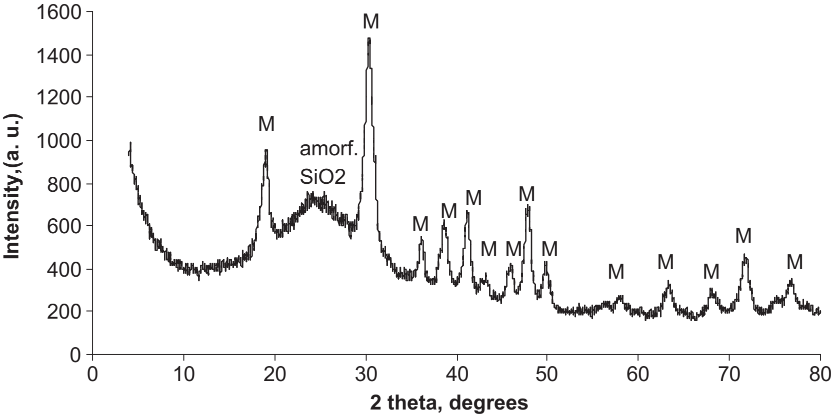


Fig. 3. X-ray of burned mullite wool waste (M – mullite).

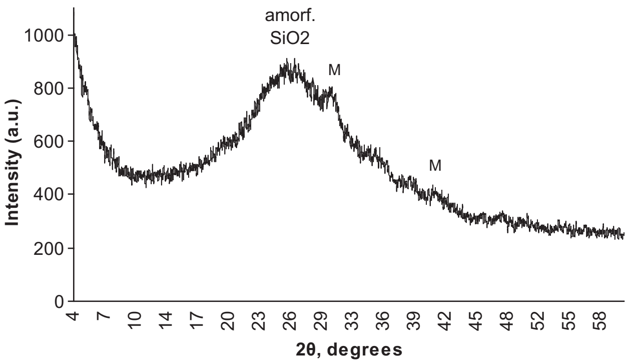


Fig. 4. X-ray of unburned mullite wool (S – amorphous SiO_2, M – mullite).

for 28 days according to EN 12390-5. The used compressive device satisfied the requirements of the standard, Part 4: Compressive strength – Specification for testing machines. The accuracy of the compressive strength machine was ⩽2%. Distribution of the results was evaluated according to standard deviation.

The ceramic samples with dimensions of 70 × 70 × 70 mm were shaped manually using the following raw materials: clay (which is hydromicous, easily fusible), quartz sand, chamotte, and the mullite wool waste. Considering our previous findings [1,2], 8 compositions of formation mixture were selected and are presented in Table 9.

The chemical composition of clay is shown in Table 10, the granulometric composition in Table 11. The used clay was sifted through 0.63 mm sieve; other components were sifted through 1.25 mm.

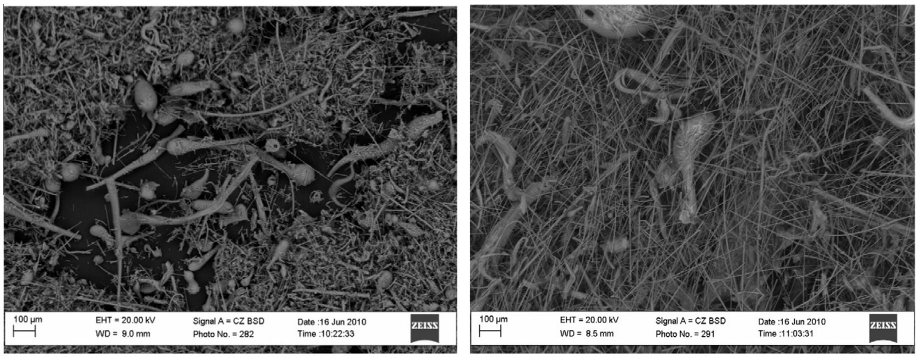
The X-ray composition of chamotte is presented in Fig. 6. The analysis of the powder was performed in phases using the method of X-ray diffraction phase based research. The main instrument used was the diffractometer DRON-7; cobalt anode was applied, and the length of wave was $\lambda = 0.1792$ nm. The diffractograms were decoded according to the standard tables (presented in the literature [24,25]), in which the values of distances between the planes *d* and the relative intensity *I* were evaluated.

The samples made of the above mentioned raw materials were dried naturally. Then, they were dried in the chamber to a constant weight. After drying, the samples were burned at the temperature of 1050 °C and 1080 °C, keeping them at this temperature for 4 h. The rate of temperature increase was 0.9 °C/min, and the rate of temperature decrease was 1.1 °C/min. The total burning time was 40 h. After burning the samples, their physical mechanical and structural properties were determined.

The density and water absorption of the ceramic samples were tested following standard LST EN 771-1+A1: 2005. Compressive strength of ceramic samples was tested according to LST EN 772-1. The exploitation frost resistance was forecasted according to the methodology of parameters of structure [26–28], conforming LST 1413.12:1998.

3. Experimental results

The X-ray pictures of the most characteristic concrete batch samples (without waste and with 8% of burned and unburned waste) are given in Figs. 7–9.



(a) (b)

Fig. 5. Microstructural picture of mullite wool waste (a – burned, b – unburned).

Table 8
Compositions of concrete mixtures.

Concrete mark	Portland cement, kg/m^3	Sand, kg/m^3	Gravel, kg/m	Burned mullite wool waste, kg/m^3	Unburned mullite wool waste, kg/m^3	Water, kg/m^3	Superplasticiser, kg/m^3	*W/C*
K	266	980	952	0	0	170	1.60	0.64
N2	265	957	948	19	0	169	1.59	0.64
N4	284	913	922	38	0	182	1.55	0.64
N6	285	896	925	57	0	182	1.55	0.64
N8	320	833	879	73	0	204	1.48	0.64
N10	337	797	860	89	0	215	1.44	0.64
ND2	281	922	913	0	19	180	1.53	0.64
ND4	319	868	877	0	36	204	1.47	0.64
ND6	381	776	801	0	49	243	1.35	0.64
ND8	406	723	763	0	63	259	1.28	0.64

Table 9
Compositions of ceramic formation mixture.

Ceramic formation mixture	Burning temperature, °C	Clay, %	Sand, %	Chamotte, %	Unburned mullite wool waste, %
1	1050	80	15	5	0
2	1050	80	10	5	5
3	1050	80	5	5	10
4	1050	80	0	5	15
5	1080	80	15	5	0
6	1080	80	10	5	5
7	1080	80	5	5	10
8	1080	80	0	5	15

Table 10
Average chemical composition of clay.

SiO_2	$Al_2O_3 + TiO_2$	Fe_2O_3	CaO	MgO	K_2O	L. O. I.
66.33	15.8	6.42	1.80	2.72	1.63	5.30

Table 11
Average granulometric composition of clay.

Quantity of sand fraction (particles larger than 0.05 mm), %	Quantity of dust fraction (particles within the size range of 0.05 to 0.005 mm), %	Quantity of clay-rich fraction, (particles smaller than 0.005 mm), %
23.93	34.03	42.04

The portlandite forms and the minerals existing in fillers (feldspars, dolomite, quartz and calcite) prevail in all concrete batches. The intensity of mullite peaks is higher for the samples with unburned mullite wool. Mullite is a thermodynamically stable mineral, improving the strength and durability of materials.

The microstructural investigations were performed after 28 days of hardening (Figs. 10 and 11).

As seen in Figs. 10 and 11, the mullite wool waste distributed unevenly in a concrete mixture. Its surface is very smooth therefore the whole fibre joins the cement stone with difficulty. Usually the sides of mullite wool attach to the cement stone. It was noticed that the cement matrices form and join more and stronger on the burned mullite wool waste (Fig. 10b).

The slump of the control mixture was 25 mm. The slump of concrete mixtures with unburned mullite wool was 15 mm, for the mixture with 8% waste – 12 mm. The slump of concrete mixtures with burned mullite waste ranged between 12 and 16 mm. This demonstrates that all mixtures are assigned to slump class S1.

The dependence of density of concrete mixture on the amount of waste is shown in Fig. 12. It can be seen that the density of the concrete mixture with burned mullite wool decreases slowlier. Adding 10% of waste into a mixture decreases density by 3.4%. The density of the concrete mixtures with unburned mullite wool decreases linearly. Adding 8% of waste decreases density even by 7%. The density decreases because the waste is replaced by part of sand, which is much heavier. The unburned wool is lighter than the burned one; therefore in this case the density of concrete mixtures decreased more.

Afterwards the physical mechanical properties of the hardened concrete were analysed and are presented in Table 12.

The density of the hardened concrete with burned mullite wool waste decreased approximately 3%, with the unburned one 6.6%. However, the compressive strength increased. Adding 10% of burned mullite wool waste, the compressive strength increased 7.7% after 7 days and 3.2% after 28 days. Adding 6% of unburned

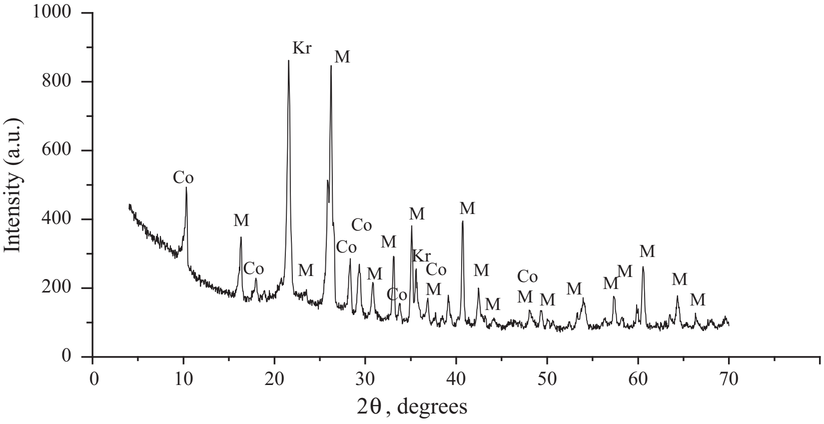


Fig. 6. X-ray diagram of chamotte (M – mullite, Kr – cristobalite, Co – cordierite).

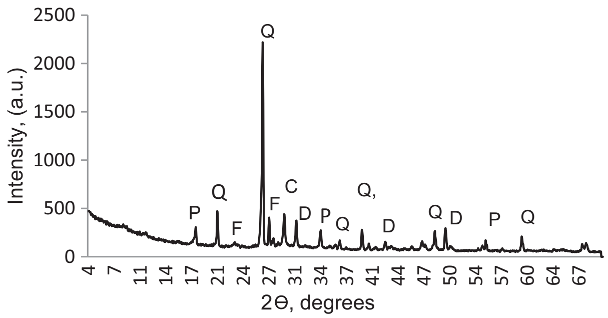


Fig. 7. X-ray of concrete without waste (P – portlandite, Q – quartz, F – feldspar C – calcite, D – dolomite).

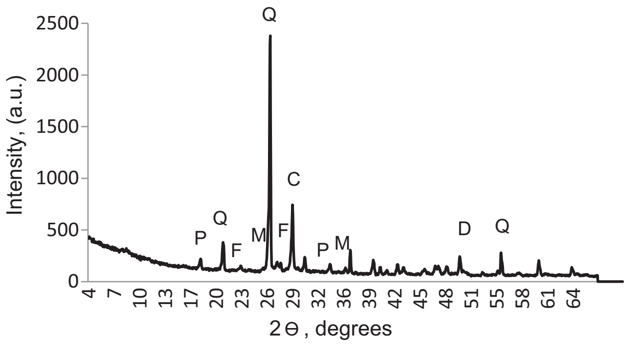


Fig. 8. X-ray of concrete with 8% of burned mullite wool (P – portlandite, Q – quartz, F – feldspar, C – calcite, D – dolomite, M – mullite).

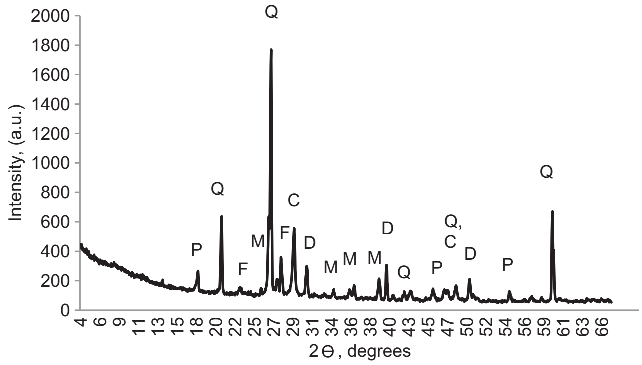


Fig. 9. X-ray of concrete with 8% of unburned mullite wool (P – portlandite, Q – quartz, F – feldspar, C – calcite, D – dolomite, M – mullite).

mullite wool waste the compressive strength increased 4.2% after 7 days, and decreased 1.7% after 28 days. The bending strength in case of burned mullite wool waste being used almost did not change, while adding the unburned mullite wool waste decreased the bending strength. The waste is lightweight additive which absorbs water; therefore it decreases density and increases absorption. However, its fibre structure allows keeping and even increasing the strength. The compressive strength is obtained larger with the burned mullite wool as this wool better attaches to the cement stone.

The unburned mullite wool mixes more difficultly and distributes not so evenly, therefore cement matrix does not cover each of its particles and the compressive strength might decrease.

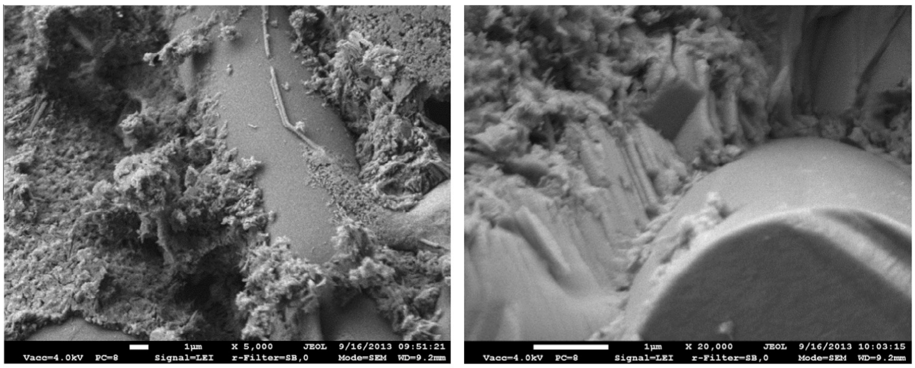
It is also important to consider the higher amount of the cement used to keep the constant *W*/*C* ratio and the slump of a mixture. The dependence of the cement quantity on the amount of waste in a mixture is given in Fig. 13.

With the rise in the quantity of waste in a mixture, the amount of cement also increases. This is because of the fact that this material absorbs water intensely and it is very difficult to obtain the analogous slump. The waste of unburned mullite wool absorbs water more and therefore significantly larger amount of cement is necessary to produce concrete of the same strength. Therefore this waste is more suitable for the manufacture of concrete of lower marks. Using 6% of the burned mullite wool waste, the quantity of cement was increased by 10%, and the concrete mark remained the same. Therefore this waste can be also used for the concrete of the normal strength.

The dependence of the density of ceramic samples on the amount of mullite wool waste and burning temperature is presented in Fig. 14.

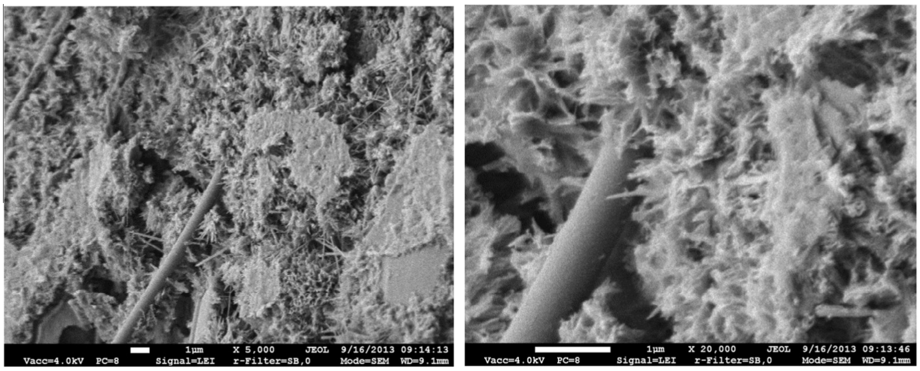
Fig. 14 shows that increasing the amount of waste in a mixture the density of ceramics decreases linearly. The decrease in density could be explained by the low density of mullite wool. The density of the unburned mullite wool is approximately 200 kg/m^3. Increasing the burning temperature from 1050 °C to 1080 °C, the density of all batches increased 7–9%. The increase in density due to temperature can be explained by a higher degree of sintering; the total shrinkage of the samples increased about 30%. Because the density of ceramic samples was decreasing linearly with the growing amount of waste, it was expected that the water absorption would increase linearly, but that did not happen (Fig. 15).

Fig. 15 shows that after burning of samples at the temperature of 1050 °C the water absorption increased when up to 10% of mullite wool waste was used and began to decrease when a larger amount was added. The similar influence of the mullite wool waste additive was noticed after burning the samples at the temperature of 1080 °C. However, in this case the decrease in water absorption



(a) (b)

Fig. 10. Microstructural view of concrete with 8% of burned mullite wool.



(a) (b)

Fig. 11. Microstructural view of the concrete with 8% of unburned mullite wool.

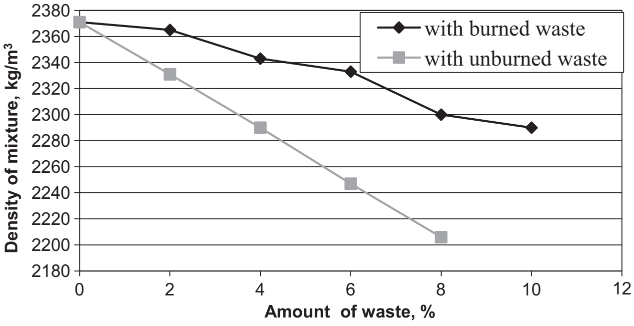


Fig. 12. Dependence of concrete density on the amount of waste in a mixture.

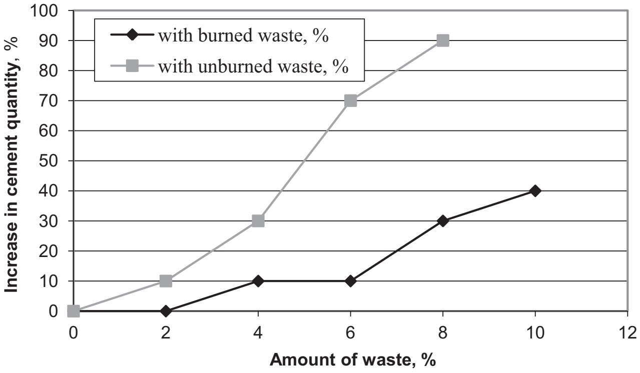


Fig. 13. Dependence of the increase in cement quantity on the amount of waste in a mixture.

was recorded when more than 5% of mullite wool waste was added. This interesting effect can be explained by the fact that adding a small amount of the waste the more closed pores form and there are small changes in the structure of ceramics. Increasing the amount of mullite wool waste in a mixture leads to the formation of more small closed pores (Fig. 16).

The dependence of the compressive strength of ceramics on the unburned mullite wool waste and burning temperature is presented in Fig. 17.

This figure shows that the compressive strength of ceramic samples decreases by adding up to 5% of mullite wool waste, while increasing the amount of waste it begins to grow again. After burning the semi-finished products of ceramics at the temperature of 1080 °C and adding 15% of wool waste, their compressive strength becomes almost the same as the compressive strength of control samples. This shows that in terms of the strength such waste can be used to produce ceramic products of high-quality. The increase in strength can be explained by the changes in the structure of ceramics because mullite wool waste has good adhesion to ceramic matrix and plays the role of reinforcement.

Other determined structural parameters of ceramics are presented in Table 13.

Table 13 shows that with the increase in burning temperature from 1050 °C to 1080 °C, the effective porosity decreased about 35%, porous space reserve increased approximately 50%, relative wall thickness of pores and capillaries increased approximately 60%, and capillary rate of mass flow decreased significantly. It happened because more liquid phase is produced when samples are burned at higher temperature. The liquid phase partially fills the pores, there is less open system of pores and capillaries, and the sample shrinks. According to the parameters of structure the

Table 12
Physical and mechanical properties of concrete.

Concrete mark	Concrete density, kg/m^3	Compressive strength after 7 days, MPa	Compressive strength after 28 days, MPa	s_e of compre-ssive strength MPa	Flexural strength, MPa	s_e of flexural strength, MPa	Water absorption, %
K	2370	25.6	33.83	0.36	9.54	0.89	4.65
N2	2360	25.25	32.66	0.85	9.57	0.26	5.46
N4	2340	26.31	32.07	0.37	9.99	0.26	6.11
N6	2346	25.26	31.88	1.52	9.79	1.04	6.17
N8	2310	27.56	34.77	1.87	9.42	0.56	6.82
N10	2300	27.58	34.9	2.61	9.73	0.24	7.24
ND2	2317	25.64	31.57	2.50	9.00	0.39	6.18
ND4	2305	25.34	33.18	2.21	8.13	0.37	6.49
ND6	2253	26.68	33.24	2.58	8.54	0.80	8.16
ND8	2214	26.46	29.69	0.65	7.80	0.33	9.27

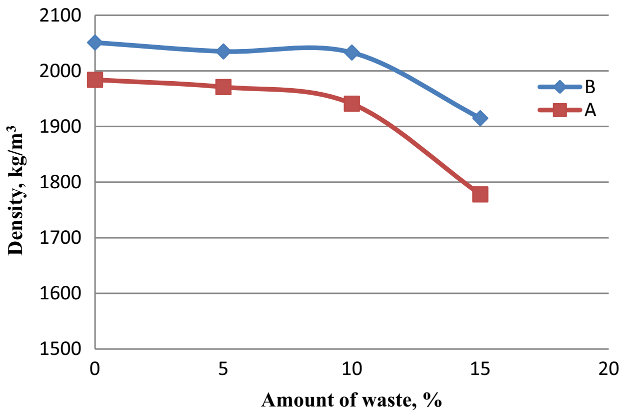


Fig. 14. The dependence of ceramics density on the amount of mullite wool waste and burning temperature (A – after burning at 1050 °C, B – after burning at 1080 °C).

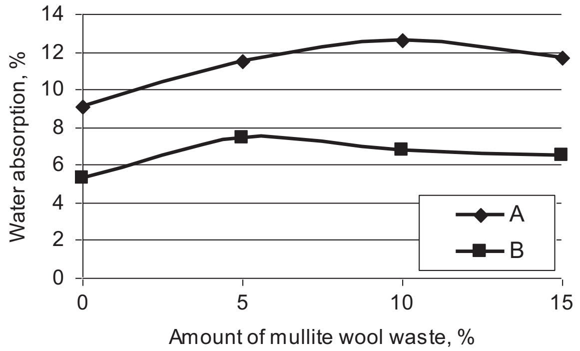


Fig. 15. The dependence of water absorption (determined after 72 h) on mullite wool waste and burning temperature (A – after burning at 1050 °C, B – after burning at 1080 °C).

exploitation resistance to frost was forecasted (when one half of the sample is being cooled, and the other is insulated, there is a targeted water inlet and cooling). The frost resistance according at the beginning of decomposition (up to 3% of the surface decomposition) and at the end of decomposition (when the entire surface decomposes) is presented in Fig. 18.

The greater frost resistance was obtained for all batches when the samples were burned at higher temperature. This was due to the higher sintering of samples and formation of more closed system of pores and capillaries. The highest frost resistance was obtained for the samples where 10% of sand was replaced by the unburned mullite wool waste. This can be explained by the largest relative wall thickness of pores and capillaries and the smallest capillary mass flow rate obtained for this batch. Therefore, the samples of this batch absorbed minimum water according to irrigation direction. The forecasted frost resistance of these samples was greater than 250 cycles at the beginning of decomposition and more than 400 cycles at the end of decomposition. Such ceramics can be used for facade buildings.

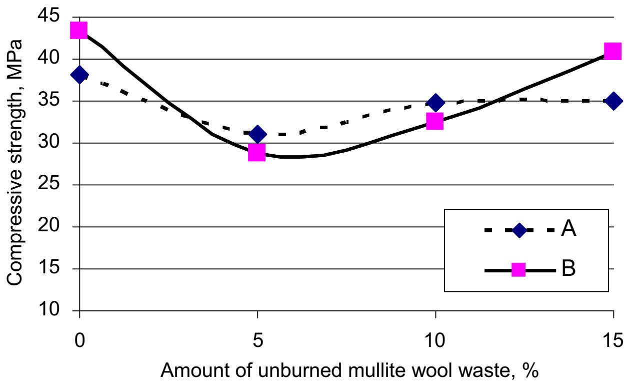


Fig. 17. The dependence of the compressive strength of ceramics on the amount of unburned mullite wool waste (A – after burning at 1050 °C, B – after burning at 1080 °C).

Table 13
Physical and structural parameters of ceramic samples.

Formation mixture	Burning temperature, °C	We, %	N, units	R_p, %	D, %	g, g/cm^2
1	1050	16.85	0.844	36.63	2.79	0.377
2	1050	20.96	0.159	26.02	2.29	0.836
3	1050	21.46	0.685	26.98	2.31	0.688
4	1050	22.53	0.383	34.86	2.15	0.736
5	1080	10.21	0.609	49.13	4.59	0.216
6	1080	13.38	0.536	44.80	3.59	0.276
7	1080	13.12	0.661	45.89	4.48	0.174
8	1080	15.76	1.012	47.48	3.25	0.257

W_e – effective porosity, N – structural inhomogeneity, R_p – reserve of pore volume, D – relative wall thickness of pores and capillaries, g – capillary rate of mass flow under normal conditions.

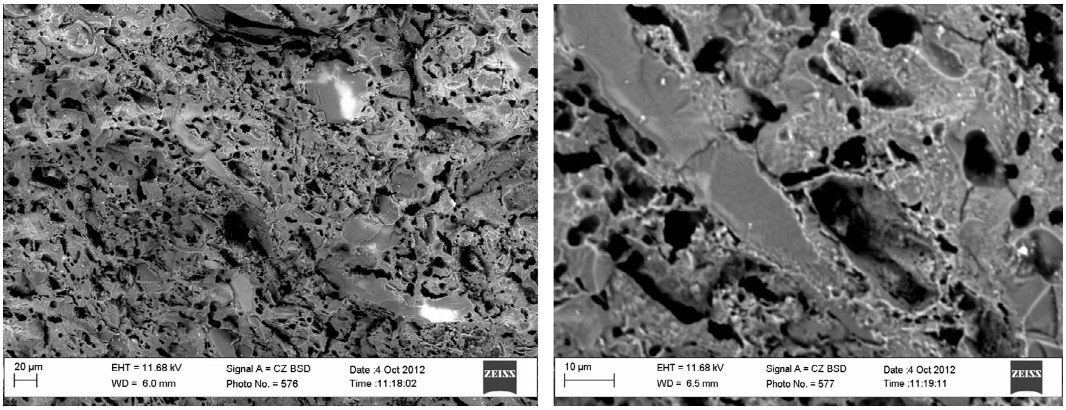


Fig. 16. Microstructural image of ceramics with 15% of unburned mullite wool waste.

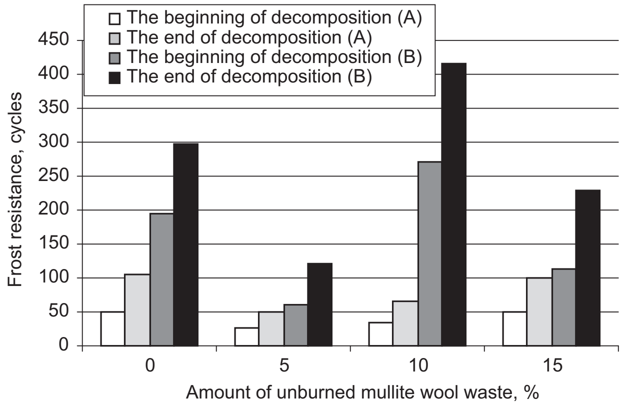


Fig. 18. The dependence of forecasted frost resistance on the amount of unburned mullite wool waste (A – after burning at 1050 °C, B - after burning at 1080 °C).

4. Conclusions

1. According to the performed concrete tests considering the compressive and bending strength of samples after 28 days of hardening the most optimum quantity of mullite wool in a concrete mix is 10% of sand mass. The average compressive strength of these samples was 34.9 MPa, bending strength 9.73 MPa. The bending strength almost did not change when the maximum amount of burned mullite wool (10%) was used. Adding 8% of the unburned mullite wool waste decreased the bending strength by 18.2%. Adding 8% of the unburned mullite wool to a concrete mixture decreased the average compressive strength, bending strength and density. The water saturation increased twice.
2. Summarising the X-ray analysis of concrete samples, it can be stated the in addition to traditional hydration products, the mullite is found in the mortar part of concrete.
3. It is beneficial to use mullite wool waste in the manufacture of ceramic products because of its positive impact on the ceramic properties and the possibility to avoid overloading of landfills. When the optimum burning temperature is 1080 °C, a significantly higher frost resistance, compressive strength and lower water absorption of ceramics are obtained.
4. By increasing the amount of this waste in a formation mixture, the density decreases linearly. The water absorption and the compressive strength changes parabolically. The minimum value of the compressive strength is obtained by using 5–8% of waste. Increasing the amount of waste in a mixture the compressive strength begins to increase. The maximum water absorption is obtained when the amount of waste in a mixture is 5–10%. Increasing the amount of waste the water absorption begins to decrease.
5. The forecasted frost resistance of ceramics with 10% of waste (samples burned at 1080 °C temperature) was greater than 250 cycles at the beginning of decomposition and more than 400 cycles at the end of decomposition. Such ceramics can be used for facade buildings.

Acknowledgments

The authors gratefully acknowledge the help of the VGTU Civil Engineering Centre in providing the laboratory equipment, which was used in the present investigation.

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