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Possibilities of Plastic Waste Application in Expanded Clay Concrete

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Abstract. The article analysis the application possibility of plastic waste and their impact on the properties of expanded clay concrete. Two plastic waste are selected from SC “Plasta” (A and B types). A type waste has slimy and dense structure, B is more porous and has rough surface. Whereas the average size of waste is up to 1 cm and the bulk density is similar to that of expanded clay, these waste have replaced a part of expanded clay with the fraction of 4/8 (0%, 5%, 10%, 20%) in expanded clay concrete mixtures. Amounts of cement, fine aggregate (sand), 8/16 fraction expanded clay, water and superplasticizer in expanded clay concrete mixtures are constant. Properties of expanded clay concrete are determined and analysed as follows: density and slump of the mixture, density of the dried expanded clay concrete specimens, capillary rate, water absorption and compressive strength. Additionally, microstructure research is conducted. It is determined that using more waste (20%), by 4% denser and by 50% stronger expanded clay concrete may be obtained compared to the control specimens. To obtain expanded clay concrete with optimal properties, it is suggested to use 5% of A type waste instead of calculated amount of 4/8 fraction expanded clay. Then, the density of expanded clay concrete increases by 5% and it is equal to 1260 kg/m^3, and compressive strength is by approximately 70% greater than the one of the control specimens and it is equal to 17 MPa. Moreover, the capillary rate and water absorption decrease. When up to 10% of A type waste are used, mixture slump increases and workability improves, therefore, the obtained specimens are easy to form. Microstructure analysis shows that there is sufficient adhesion between aggregates, waste and cement stone. The microstructure of cement stone under different loadings of waste is different. The densest structure has specimens with 5% of A type waste. The same minerals, i.e. portlandite, ettringite, calcite and calcium hydro silicates are determined in specimens from all batches. After conducting statistical analysis of the obtained compressive strength results, mathematical second degree polynomial dependence is concluded. It allows prediction of expanded clay concrete’s compressive strength depending on the amount of waste. Determination coefficient of the equation is equal to 0.845. It can be seen from the obtained equation that the compressive strength of expanded clay concrete increases under a certain amount of waste and then, it decreases.

1. Introduction

50% of solid municipal waste emerge from the used packaging (mainly from polymeric and combined which are not affected by biological degradation, decomposition and corrosion processes and may retain many decades in the soil). Worldwide plastic production has developed from 1.5 (1950) to 245 million tonnes per year (2008). 60 million tonnes are produced in Europe alone. According to calculations (under normal conditions), 65 million tonnes of plastic will be made in 2020, and up to 2050, worldwide plastic production may be tripled. The main factor determining the increase is by 24% increased packaging sector and without outbreaks strengthening plastic waste accumulation tendency in Europe. If measures are not taken and production scale increases, the amounts of plastic waste in EU will rise [1]. State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

SC "Plasta" is one the largest European polyethylene waste recycling and plastic production manufacturers. 30 million tonnes of plastic waste are recycled annually.

It would be useful to recycle such waste in building industry. In recent decades, variety of scientific researches related to the use of different types of plastic waste for the production of concrete and mortar have been conducted [2]. Researchers [3–7] analyse the secondary use of packaging and other plastic waste: lightweight concrete's expanded clay pellets from waste automotive plastic and clay [3], polymer concrete containing electronic plastic waste [4], lightweight concrete made from cable, polystyrene and ethylene vinyl acetate waste [5], recycled polyolefin waste [6], various plastic waste in concrete [7].

Algerian scientists [8] have tested thermo-physical and mechanical characteristics of sand-based lightweight composite mortars with recycled high-density polyethylene (HDPE). The bulk density of HDPE is 0.92 g/cm^3, particle size ≤ 3.15 mm. Natural sand is replaced with HDPE waste fractions of 0%, 15%, 30%, 45% and 60%. The results have shown that increasing amount of HDPE waste reduces the density of mixtures and hardened specimens; although, HDPE waste negatively affect mechanical properties of mortar specimens. Replacing sand with polyethylene waste, compressive strength after 3, 7, 28, 90 and 180 days reduces compared to control specimens. The reduction in compressive strength is determined by low adhesion strength between HDPE plastic waste surface and cement stone. Similar researches are conducted by Turkish scientists [9], who have tested the shredded waste PET bottles as aggregate in lightweight concrete. The size of shredded PET granules used in the preparation of mortar mixtures are between 0 and 4 mm and its specific gravity is 1.27 g/cm^3. Compressive strength results after 1, 3, 7, 28, 90 and 180 days show that after 28 days of hardening, the property reaches its value of (22.4–28.3) MPa. The density of dried specimens ranges from 1552 kg/m^3 to 1840 kg/m^3 and water absorption - from 11.9% to 14.8%.

Scientists [10] have determined that reused PET waste may be incorporated as binding material for the production of ductile mortars. The article [11] analysis the high density polyethylene waste which is mixed with Portland cement in order to investigate the possibility to produce plastic cement and study the effect of replacing sand by fine polyethylene waste with different percentage on the properties of product. The results show that there is a possibility to produce plastic cement from 60% of polyethylene waste and 40% of Portland cement. In addition, their density decreases, ductility increases and workability improves.

Researchers [12] have studied (2%, 4% and 6%) PE polymer particles as a replacement for cement, water-to-cement (W/C) ratios, ranging from 0.48 to 0.54 with a constant workability (30%), are used in the preparation of the composite mortars. The size distribution of the non-soluble PE polymer particles ranges from 80 mm to 0.5 mm. Recycled reinforcing mortars incorporated with 2 vol.% of PE polymer particles can be qualified as an advantageous and promising composite material in the concrete field repair in aggressive media.

Authors from Bangladesh and Canada [13] have tested the effects of waste PET as a coarse aggregate on the properties of fresh and hardened concrete. To investigate the performance of PET aggregate on the properties of fresh and hardened concrete, five mixture types are selected where the natural coarse aggregates (brick chips) with PET coarse aggregates in the amounts of 0 vol.%, 20 vol.%, 30 vol.%, 40 vol.% and 50 vol.% are used. Concrete mix designs are used for three different W/C ratios, and they are 0.42, 0.48, and 0.57. Research results show that increasing the W/C ratio increases the slump of mixture, reduces compressive strength and density of specimens. When W/C is 0.48, the slump of mixture is obtained to be from 20 mm to 50 mm, compressive strength is in the range of (20–28) MPa and density - (1950–2050) kg/m^3.

PET waste can be used as fine aggregate in concrete. Iranian scientists [14] have shredded PET waste up to 7 mm and used them as a fine aggregate (5%. 10% and 15%) in concrete mixtures. Concrete specimens in 5% sulphur solution have been maintained for 15, 30 and 60 days. Specimens with the greatest amount of PET waste are characterized by the lowest mass loss.

Low density polyethylene (LDPE) waste may be used in normal concrete [15]. Cement amount in all mixtures is the same - 380 kg/m^3, W/C ratio - 0.46. Compressive strength after 28 days of prepared control cubes with 0%, 0.4%, 0.6%, 0.8% and 1% (by weight) of LDPE waste is 26.7 MPa, with 0.4% - 32.7 MPa, with 0.6% - 35.9 MPa and with 0.8% - 36.1 MPa.

Other authors have used high density polyethylene (HDPE) fibre (it is obtained by cutting plastic buckets and dishes) in concrete [16]. The length of fibres is 60 mm, width - 4 mm, thickness - 1 mm. For the production of concrete, amounts of fibres are used as follows: 0%, 25%, 50%, 75% and 100%. Research results show that increasing amount of fibres in concrete mixture reduces compressive strength. 25% of fibres allow obtaining compressive strength equal to 21.42 MPa. Although, other results are obtained by the scientists from United Kingdom [17], the diameters of their prepared HDPE fibres are 0.25 mm and 0.40 mm. Three series of concretes are prepared with amounts of fibres equal to 0.40%, 0.75% and 1.25%. The greatest results are obtained for specimens for which production 0.40% of fibres with the diameter of 0.25 mm are used. The compressive strength of such specimens after 28 days of hardening is 34.3 MPa.

Literature review shows that reuse of plastic waste in concrete mixtures may have positive effect on the properties of concrete, and such concrete is environmentally friendly building material.

This work analysis the possibility to utilize plastic waste in expanded clay concrete. The main aim of this work is to investigate two types of plastic waste and evaluate their impact on physical, mechanical properties and structure of expanded clay concrete.

2. Materials and research methods

For the formation of lightweight concrete specimens, raw materials are used as follows: cement, natural sand, expanded clay with different fractions, new generation superplasticizer, plastic waste and water. The main raw material - Portland cement CEM I 42.5 R, which conforms to the requirements of standard LST EN 197-1. The main characteristics of Portland cement are presented in table 1.

Mineralogical composition of cement CEM I 42.5 R: C3S - 62.5 %, C2S - 9.6 %, C3A - 7.1 %, C4AF - 11.5 %.

Fine aggregate - natural sand, which conforms to the requirements of standard LST EN 12620. Fraction is 0/4. Research data of sand physical properties are presented in table 2.

Table 1. Characteristics of Portland cement

Particles density, g/cm^3	Bulk density, g/cm^3	Fineness, cm^2/g	Compressive strength after 2 days, MPa	Compressive strength after 28 days, MPa
3.1	1.1	3700	20	61

Table 2. Physical properties of sand

Characteristic	Tests results
Particles density, kg/m^3	2500
Water absorption, %	0.57
Bulk density, kg/m^3	1575

Properties of expanded clay conforming to the requirements of standard LST EN 14063 are presented in table 3.

Table 3. Properties of expanded clay

Characteristic	Fraction	Tests results
Bulk density, kg/m^3	4/8	290
Bulk density, kg/m^3	8/16	250
Particles density, kg/m^3	4/16	410
Water absorption after 24 h, %	4/16	17.5
Compressive strength, MPa	4/8	1.97
Compressive strength, MPa	8/16	1.11

New generation superplasticizer Master Glenium sky 628 based on polycarboxylates is used in all mixtures. It is of liquid state; its density is in the range of (1.05–1.09) g/cm^3. Superplasticizer conforms to the provisions of LST EN 934-2. Water is used according to the requirements of LST EN 1008.

Two types of waste are used from SC "Plasta". The general view of the mentioned waste is presented in figure 1. A type waste (shredded HDPE - high density polyethylene) is produced from plastic packaging waste. Processing stages of this type waste - sorting, shredding (coarse and fine fractions), washing and drying. B type waste (LDPE - low density polyethylene) is produced from plastic covers' waste.

Figure 1. Image of tested waste

It can be seen from figure 1 that the average size of waste is up to 1 cm. A type waste has slimy and dense structure, B is more porous and has rough surface. The bulk density of waste is 260 kg/m^3.

Compositions and densities of expanded clay concrete mixtures, determined according to LST EN 12350-6, are presented in table 4. Expanded clay has been already saturated with water before using it in mixture (expanded clay has been immersed for 24 hours). The amount of absorbed water is deducted from the calculated amount of water (155 kg/m^3). The W/C ratio is 0.5. The amount of waste is calculated in percent (0%, 5%, 10%) by 4/8 fraction expanded clay mass.

It can be observed from the results presented in table 4 that the density of concrete mixture with waste, which are used instead of a fine aggregate, in all cases increases to a small amount compared to the control specimens. The difference is not high because bulk densities of aggregates vary in a small range: bulk density of waste is 260 kg/m^3 and 4/8 fraction expanded clay - 290 kg/m^3. An increase in density is determined by the shape of aggregates. Waste are more flat and squeezed in cement matrix.

Table 4. Compositions of expanded clay concrete mixtures

Designation	Composition of expanded clay concrete, kg/m³								Mix density, kg/m³
	Cement, kg/m³	Sand, kg/m³	Expanded clay 4/8, kg/m³	Expanded clay 8/16, kg/m³	Water, kg/m³	Plasticizer kg/m³	Waste A, kg/m³	Waste B, kg/m³	
K	310	680	142	142	127	3.1	0	0	1463
WA5	310	680	135	142	127	3.1	7	0	1516
WA10	310	680	128	142	127	3.1	14	0	1475
WAB10	310	680	110	142	127	3.1	14	14	1485

(100x100x100) mm sized specimens have been formed from the prepared mixture and maintained for 1 day under normal conditions and then, for 27 days in water which temperature is 20 °C. The production and hardening of concrete specimens for the determination of strength is carried out in accordance with LST EN 12390-2. Strength of concrete specimens is determined according to LST EN 12390-3. Density - based on the requirements of LST EN 12390-7. Water absorption - in accordance with the literature reference [18].

For the analysis of microstructure, scanning electron microscope JEOL JSM-7600F is used. Its resolution is 1.5 nm, magnification ranges from 25 to 1 000 000 times; during tests, voltage of 4.0 kV is used. The surfaces of tested specimens are coated with gold.

Data grouping and preparation for regression analysis is carried out with Microsoft Excel software. A statistical analysis of the researched indicators is carried out as per literature [19]. This function is selected to determine the mathematical relationship, which describes the distribution of data the most precisely, as well as assessing whether multi-unit correlation and determination ratios are close to one.

3. Tests results and analysis

The determined expanded clay concrete slump is presented in figure 2.

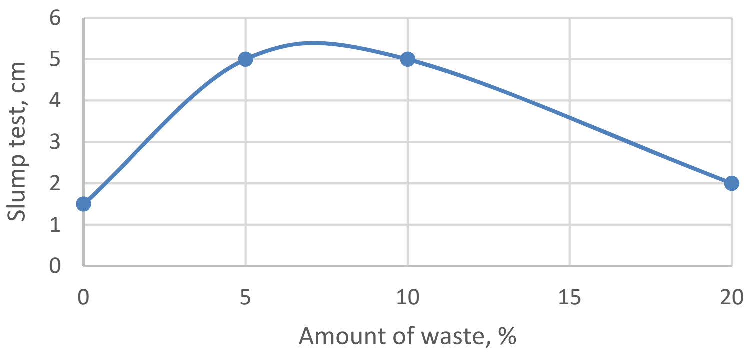

Figure 2. The dependence of expanded clay concrete slump on the amount of waste

When the amount of A type waste increases up to 10%, the slump of mixture increases as well, thus obtaining the improved mixture workability, therefore, it is easier to form specimens. Under A type waste amount of 5% and 10%, three times increased slump can be observed. An increase in slump is obtained because A type waste is incapable to absorb water. Mixture with 10% of A type waste and 10% of B type waste has a slump which is similar to the control specimens. The effect may be explained by the B type waste roughness and capability to absorb water into pores and capillaries.

Figure 3 shows how the density of dried expanded clay concrete changes when plastic waste are added into mixture. Under 5% of A type waste, the density of expanded clay concrete increases approximately by 5% what can be explained by the flat-shape of particles which can easily press itself into cement matrix. Whereas the amount of waste is small, they are easily mixed and homogeneously dispersed as well as sufficiently inserted into cement matrix, thus increasing the density of expanded clay concrete. When 10% of A type waste are added, higher density is obtained compared to the control specimens, however, it is lower when 5% of A type waste are used. Consequently, 10% of waste may be immoderate due to uneven distribution, worse adhesion and appearance of pores as well as cavities around waste particles.

Interesting results are obtained when B type waste is used. Compared to the control specimen, the density increases by approximately 4%. Therefore, B type waste helps to fill the appearing cavities which form when A type waste is used (10%).

Figure 3. The dependence of expanded clay concrete density on the type of waste and their amount

The dependence of expanded clay concrete compressive strength on the amount of waste is presented in figure 4.

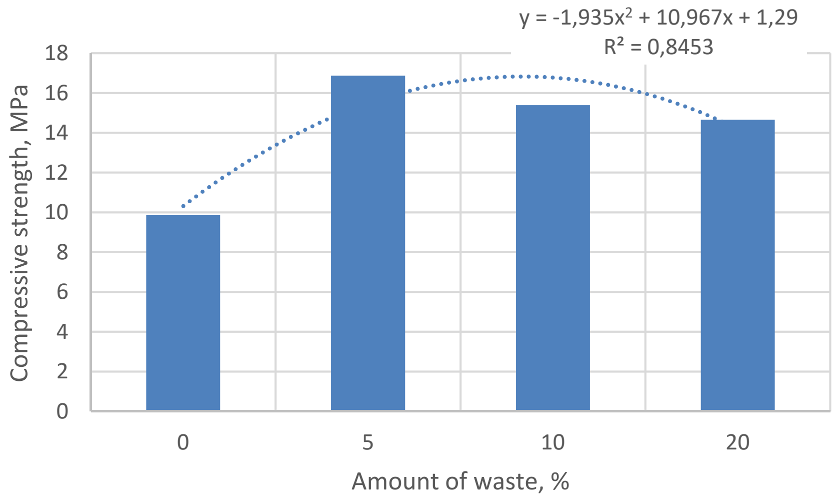

Figure 4. The dependence of expanded clay concrete compressive strength on the amount of waste

It can be seen from figure 4 that plastic waste in all cases increase the strength of expanded clay concrete. The highest strength, which is 16.9 MPa, is obtained when 5% of A type waste are used. Such strength is approximately by 70% higher than the strength of the control specimens (approx. 10 MPa). Specimens from this batch have the highest density and mixture slump as well. In order to preliminary predict the compressive strength of expanded clay concrete, mathematical dependence, evaluating the amount of waste in mixtures, is concluded. The most suitable mathematical model for the description of the dependence is a second degree polynomial with the lowest average standard deviation and the highest determination coefficient. Therefore, the compressive strength of expanded clay concrete fluctuates according to the parabola curve when the amount of waste increases: it increases up to a certain point and subsequently decreases.

In order to ascertain why the highest density and compressive strength is obtained when 5% of A type waste are added, SEM analysis is implemented. Microstructure images are presented in figures 5–6. Figure 5 shows the adhesion between cement stone, expanded clay (figure 5a) and different types of waste (figures 5b, 5c). These images show that there is a sufficient connection between cement matrix, expanded clay and plastic waste. When specimens are magnified 100 times, there is no evidence of cracks, bigger pores or other poor contact marks in contact zones.

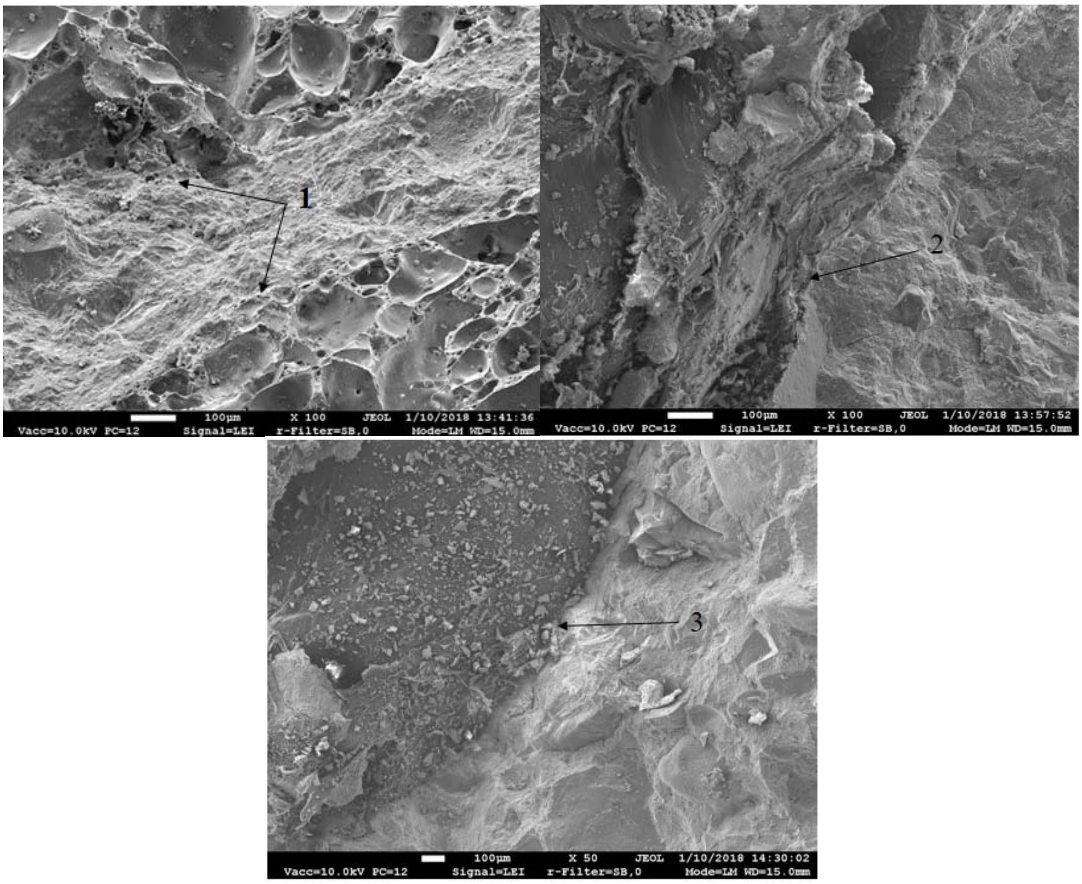

Figure 5. Image of interaction zones between aggregates and cement stone. 1 - interaction zone between expanded clay pellet and cement stone, 2 - interaction zone between A type waste and cement stone, 3 - interaction zone between B type waste and cement stone

In figure 6, the specimens are magnified 3000 times, the main cement minerals such as P - portlandite, E - ettringite, C - calcite and CSH - calcium hydrosilicates can be identified from images. Air pores, existing in cement matrix, are designated as O. From all images, practically all cement minerals can be observed, however, the structure of specimens differs. In the control specimen structure, few micron-sized pores with needle-like ettringite structure, can be observed. The structure is porous and covered by mushroom-like crystals. Whereas the structure of specimens from this batch is the most porous, compressive strength is the lowest (figure 4). Substituting 5% of expanded clay with A type plastic waste, the obtained structure is denser and there is no mushroom-like crystals (figures 6b, 6c). Figure 6b shows cement matrix structure near the expanded clay, and figure 6c - near A type plastic waste. The structure and amount of formed minerals in figure 6b and figure 6c differ, i. e. bigger blocks of portlandite and calcite form near expanded clay, less ettringite is observed. It can be explained by the fact that expanded clay originally absorbs more water and subsequently, when hydration takes place, gives away the water to cement stone. Plastic waste do not absorb water, the amount of water in that place of mixture is lower, therefore, considerably higher amount and bigger needle-like ettringite is observed. Figures 6d and 6e show microstructure when two types of plastic waste are used, i. e. A type and B type. The structure of these specimens is dense, there is practically no needle-like ettringite. Although, it can be observed from figure 6e that there are bigger pores in specimens from this batch.

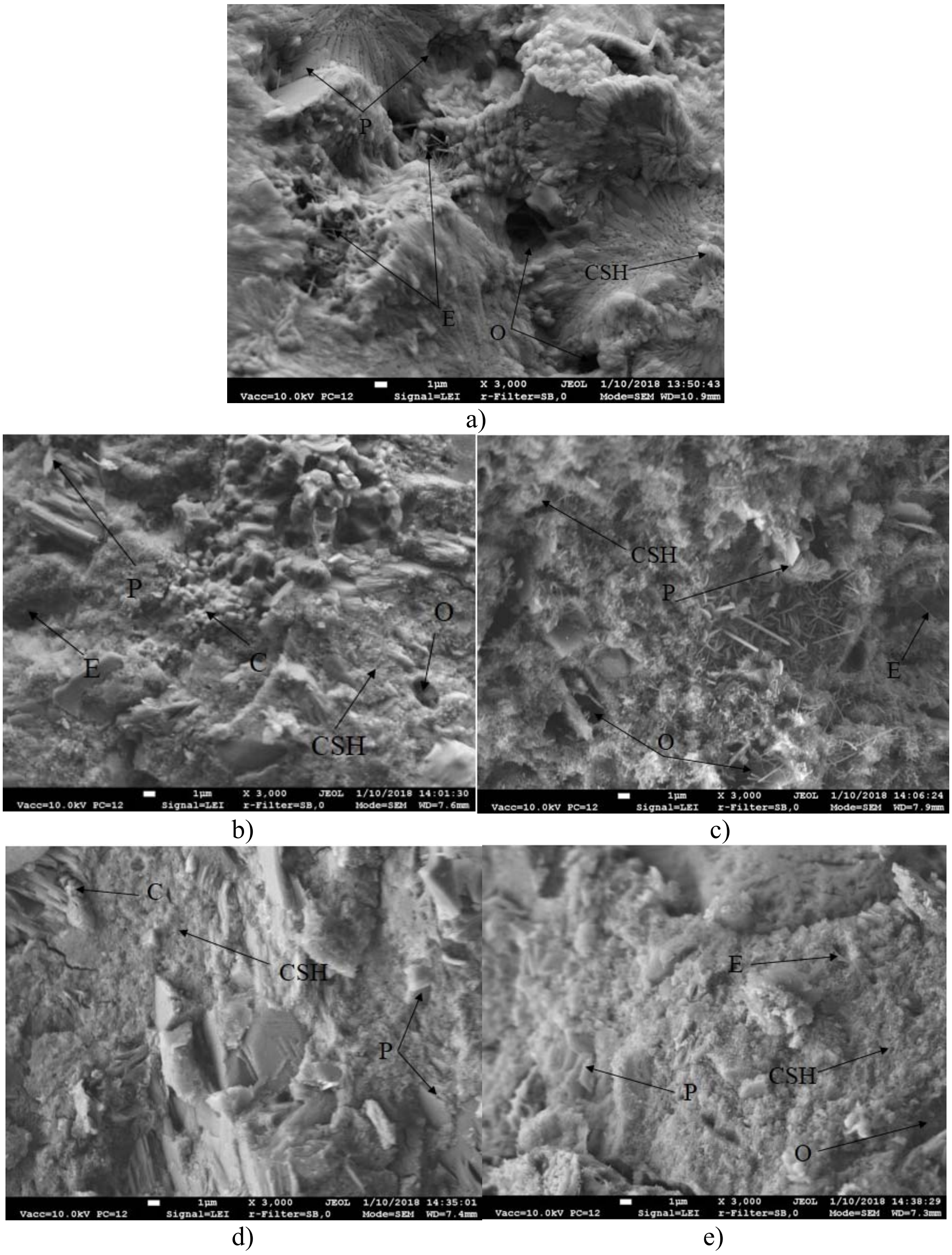

Figure 6. Microstructure images of expanded clay concrete specimens: a) control specimen, b and c) with 5% of A type waste, d and e) 10% of A type and B type waste each

Water absorption results of expanded clay concrete are presented in figure 7.

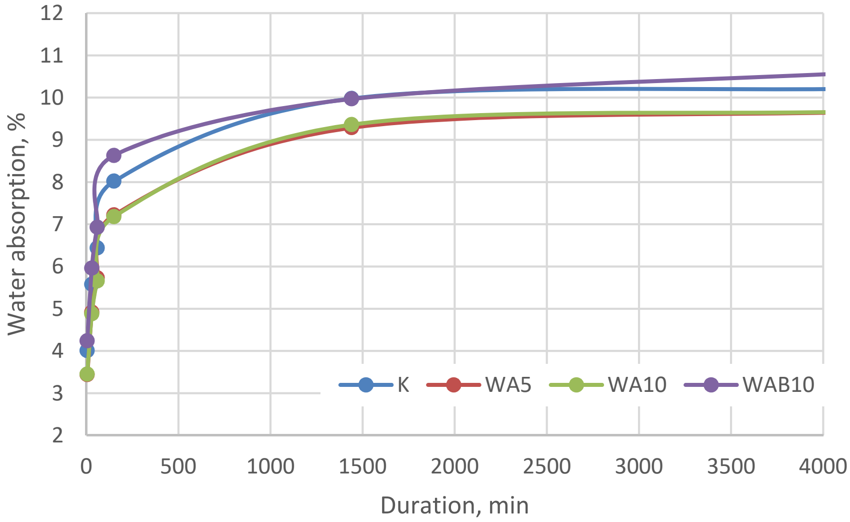

Figure 7. The dependence of water absorption on the amount of waste

In principle, water absorption of all batches is very similar. However, expanded clay concrete specimens with A type waste absorb somewhat less water (water absorption, determined after 96 hours, reduces by 5%) compared to the control specimens or specimens with B type waste. The highest water absorption is obtained for specimens where A type and B type waste are used together. There are elongated pores in microstructure of these specimens, thus assuring easy penetration of water (figure 6e).

The results of capillary rate are presented in figure 8.

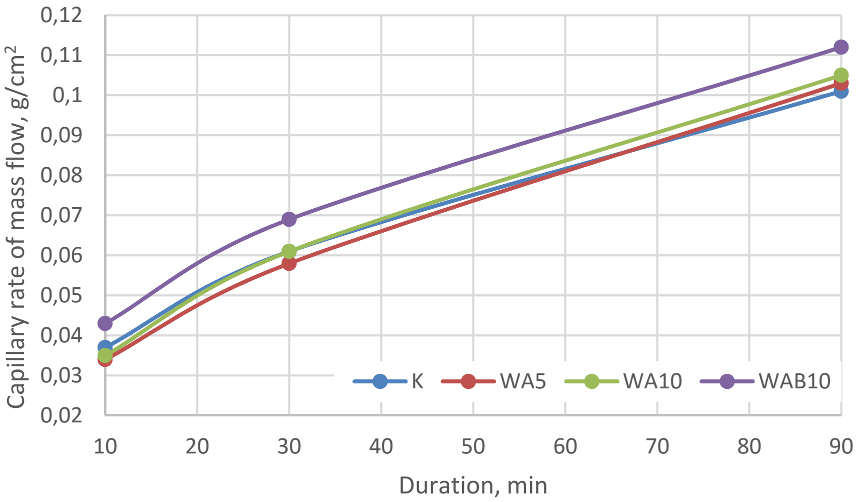

Figure 8. The dependence of expanded clay concrete capillary rate on the amount of waste

The highest capillary rate as for water absorption is obtained for specimens where A type and B type waste are used. It can be explained by elongated pores existing in microstructure of cement stone (figure 6e). Capillary rate of other batches is very similar.

4. Conclusions

It is determined that using waste as much as possible (20%), expanded clay concrete with by 4% higher density and by 50% higher compressive strength compared to the control specimens may be obtained. In order to achieve the rational properties of expanded clay concrete, it is suggested to use 5% of A type waste instead of calculated amount of 4/8 fraction expanded clay. Then, the density of expanded clay concrete increases by approximately 5% and compressive strength – by 70% compared to the control specimens, however, water absorption and capillary rate reduce. Furthermore, better workability of expanded clay concrete is obtained.

Second degree polynomial mathematical dependence is concluded. It allows prediction of expanded clay concrete's compressive strength depending on the amount of waste. Determination coefficient of an equation is 0.845. According to concluded dependence, it can be seen that compressive strength of expanded clay concrete increases under a certain limit of waste amount in mixture and subsequently decreases.

Microstructure analysis shows that there is a sufficient adhesion between aggregates, waste and cement stone. Microstructure of cement stone, when different amounts of waste are used, differs. The densest structure has specimens with 5% of A type waste. The same minerals: portlandite, ettringite, calcite and calcium hydrosilicates are determined in specimens from all batches.

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