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THE EFFECT OF POZZOLANIC ADDITIVES ON THE PERFORMANCE OF THE CEMENTITIOUS MATRIX OF RECYCLED AGGREGATE CONCRETE

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Abstract. The article presents the influence of pozzolanic additives and polycarboxylate superplasticizer on the performance of the cementitious matrix of recycled aggregate concrete. The particle size distribution by volume and surface area of fly ash and silica fume is given, and the phase composition and microstructure of cementing paste are investigated.

Keywords: fly ash, silica fume, recycled aggregate, polycarboxylate superplasticizer, cementitious matrix, concrete.

1. Introduction

Cement-based materials are widely used in various construction sectors. Concrete is the second most commonly used material after water, and due to its high structural strength and durability, it is an important component of modern infrastructure. At the current stage of concrete production, one of the main principles is sustainability, as global concrete production accounts for 8% of man-made CO_2 emissions worldwide.[1]

In the production of concrete, the main components are natural aggregates: granite crushed stone, gravel, and sand, the extraction of which is a costly process. Thus, the value of natural aggregates in the world in 2018 was about \$430 billion, and it is expected that in 2026 it will increase 1.4 times and reach \$600 billion, with about 60% of aggregates used for concrete production.[2] The decrease in carbon content of concrete is largely achieved by using different types of materials to replace cement and aggregates, which determines the production of low-carbon concrete.[3,4]

The significant amount of demolished concrete, construction waste, *etc.*[5] is a problem around the world. Crushed concrete can be used as an aggregate in concrete. About 200 million tons of construction and demolition waste are generated every year in Europe.[6] It should be noted that the significant number of civilian infrastructure facilities have been destroyed or damaged as a result of the hostilities in Ukraine. One of the possible ways of reusing concrete waste (concrete, reinforced concrete structures and products, as well as their fragments) is the production of coarse and fine aggregates for concrete.[7] The use of recycled concrete not only reduces the consumption of natural materials but also reduces CO_2 emissions. At the same time, the low characteristics of recycled aggregate concrete (RAC) limit its widespread use.[8,9]

Concrete as a heterogeneous material consists of two components that have very significant differences: the cementitious matrix and aggregates. Granite aggregates typically have higher strength, lower porosity, and an order of magnitude lower deformation than the cementitious matrix, which is formed during the hydration process and binds the aggregates together.[10,11] Characteristically, the cement fraction is limited in content (approximately 300 kg/m^3 of concrete) but has a dominant effect on the most properties of the concrete. The binder properties must be used in concrete as fully as possible, so the cementitious matrix is formed based on the "Portland cement – supplementary cementitious materials – superplasticizer" system.[12] As a result, a dense concrete structure is obtained at the meso- and microlevels. This is achieved by the following effects: high packing density of the cementitious system grains due to the use of finely dispersed compositions (physical optimization); pozzolanic reaction when using active mineral additives (chemical optimization); increased adhesion between the cementitious matrix and aggregate (optimization of the concrete mesostructure).[13,14]

One of the basic ingredients of concrete mixtures is supplementary cementitious materials (SCMs), among which fly ash and silica fume are widely used.[15,16] Fly ash (FA) is the ash collected from the exhaust gas of coal power plants. Condensed silica fume (SF) is a by-product

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of silicon production. Admixtures such as superplasticizers can be used to improve the workability and flowability of cementitious mixtures added in small amounts (1-2 %) by weight of cement.[17-19] Pozzolanic fly ash and silica fume additives perform the following main functions in cementitious systems: filling the intergranular space, improving rheological properties due to the spherical shape of fly ash particles, and accelerating the binding of portlandite by the ultrafine fraction of microsilica into high-strength calcium hydrosilicates.[20,21] Therefore, the development of efficient concretes with recycled aggregates requires the study of "Portland cement clinker – curing time regulator – active mineral additives – microfillers – superplasticizer" cementing systems. This will allow to control the processability and kinetics of structure formation, intensify the initial stages of hardening, and create a strong and monolithic structure of the cementitious matrix of concrete with recycled aggregates.[22-24]

It should be noted that the surface of concrete recycled aggregates is covered with cement mortar residues, the structure of which is porous with the formation of microcracks. This leads to their increased water absorption and reduced strength of the contact zone between the aggregate and the cement paste (interfacial transition zone, ITZ).[25,26] Multicomponent SCMs fill cement paste voids and contribute to the compactness of the ITZ structure by reacting with calcium hydroxide to form CSH gels, which, in turn, improve the macroscopic characteristics of RAC.[27] Therefore, it is important to increase the strength of the ITZ by modifying the cementitious matrix.[28] This will allow the development of low-carbon concrete with improved performance and is relevant and in line with the global concept of sustainability.

The work aims to study the effect of such pozzolanic materials of different dispersion levels as fly ash and silica fume in combination with polycarboxylate superplasticizers on the structure formation and characteristics of RAC from the macro- and microscopic standpoints.

2. Experimental

2.1. Materials

Portland limestone cement CEM II/A-LL 42.5 R was used in the studies. The mineralogical composition of Portland cement clinker is as follows (wt. %): C_3S – 62.8, C_2S – 13.4, C_3A – 6.5, and C_4AF – 12.1; content of alkaline oxides in the clinker (wt. %): K_2O – 1.1 and Na_2O – 0.17. Portland cement CEM II/A-LL 42.5 R is characterized by fractions with particle diameters of Ø5, Ø10, Ø20 and Ø60 μm, the content of which are 20.46, 35.23 and 86.34 %, respectively; the grain sizes Dv(10), Dv(50), and Dv(90) correspond to 1.6, 13.3 and 48.8 μm. The specific surface area according to Blaine is 4200 cm^2/g.

The fly ash from Burshtyn TPP and Elkem Microsilica Grade 940-U silica fume were used as pozzolanic additives. The fly ash composition is (wt. %): SiO_2 – 53.68, CaO – 3.85, Al_2O_3 – 26.02, and Fe_2O_3 – 8.92. The specific surface area of FA is 3240 cm^2/g. For silica fume, the SiO_2 content is 95.8 wt.%. The specific surface area of microsilica is 15000 cm^2/g.

To strengthen the contact zone of the cementitious matrix and aggregate in fine-grained concrete, a combined pozzolanic additive based on FA and SF was used. These ingredients were mixed in a ratio of 3:1 in a vibrating mill. Master Glenium 430 polycarboxylate ether based superplasticizer (PCE) was used in the studies. To obtain fine-grained concrete, quartz sand with a fineness modulus of 2.7 was used. As an alternative fine filler, crushed concrete waste of C20/25 strength class was used. The waste was crushed in a jaw crusher to obtain grains of various sizes and then grounded in a laboratory mill to obtain a fraction of 0.16...2.5 mm with fineness modulus of 2.75.

2.2. Methods

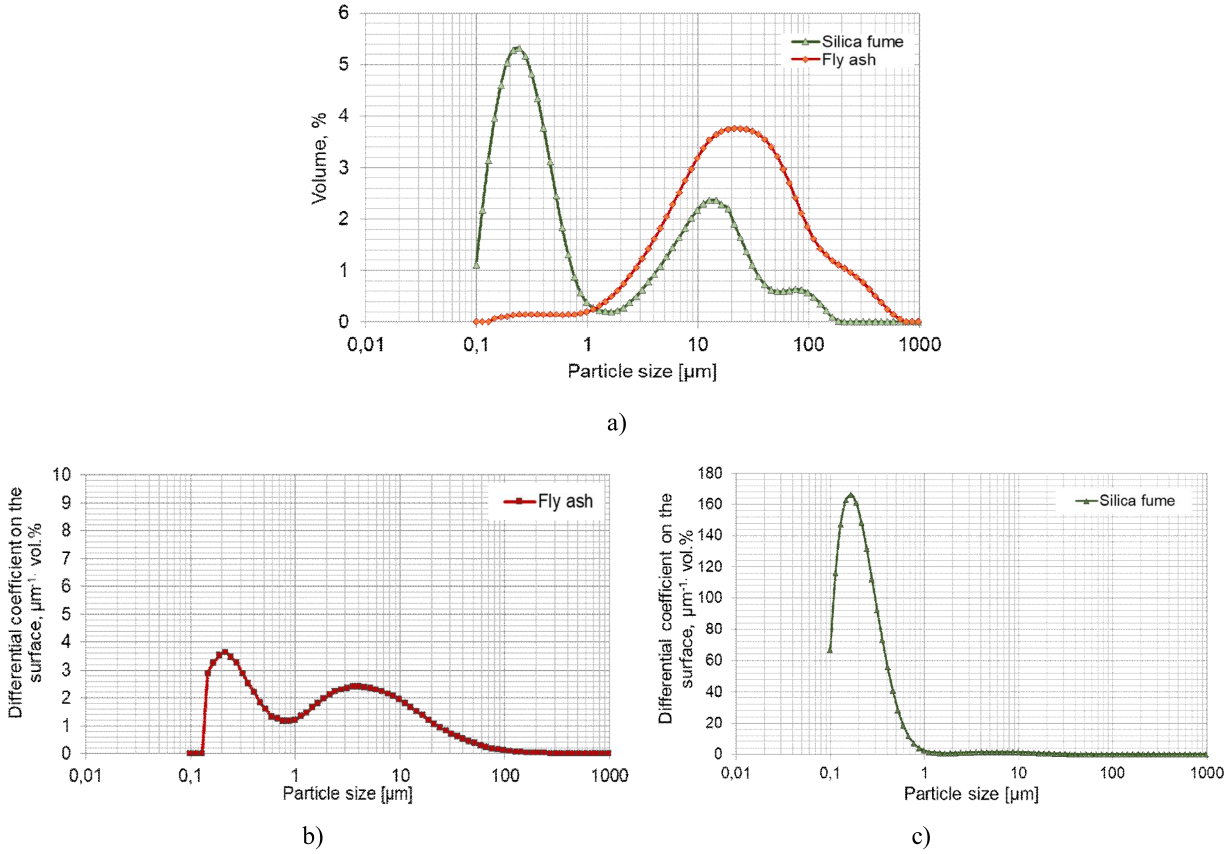
The chemical composition of the components was determined by fluorescence analysis. The laser diffraction method was used to determine the particle size distribution of cement, fly ash, silica fume, and combined pozzolanic additive. To determine the quantitative dependencies of the polymodal differential distribution of particle sizes of dispersed active mineral additives by specific surface area, the methodology for assessing surface activity was used.[29,30] X-ray diffractometry, thermogravimetry, and scanning electron microscopy were used to determine the phase composition of Portland cement and cementing systems.

The flow of the mixture and the flexural and compressive strengths of fine-grained concrete was determined according to the literature.[33] The compressive and flexural strengths of the tested fine-grained concrete under study were determined on prisms 40×40×160 mm. Samples were tested after 2, 7 and 28 days of curing.

3. Results and Discussion

To determine the effect of the pozzolanic additives on the concrete properties, the dispersion of fly ash and silica fume was studied. Using laser granulometry, it was found that for fly ash the content of fractions Ø5, Ø10, and Ø20 μm is 13.11, 28.87, and 46.88 %, respectively, and the grain sizes Dv(10), Dv(50), and Dv(90) corresponds to 4.15, 23.6, and 135.0 μm, respectively.

The average volumetric diameters by specific surface area D[3;2] and volume D[4;3] for FA are 7.16 and 53.7 µm, respectively. The maximum on the differential particle size distribution curve corresponds to 25.3 µm (Fig. 1a). For FA, the content of the fraction up to 1 µm is 2.21 % and the maximum surface activity in the bimodal distribution is K_{isa} = 3.81 and K_{isa} = 2.42 μm^{-1}·vol. % and falls on particles of 0.23 and 3.85 µm in size (Fig. 1b). The analysis of the dispersion parameters of silica fume (SSA = 15000 cm^2/g) indicates its extremely high surface activity. According to laser granulometry results, the content of an ultrafine fraction of less than 1.0 µm in size with an integral volume distribution is 59.31 wt. % for silica fume. As can be seen from Fig. 1a, silica fume is characterized by a bimodal differential distribution of particles by volume. Their highest content is characteristic of the ultrafine fraction of 0.22 µm; the presence of 10.3 µm fraction is also recorded. At the same time, the calculated value of the integral distribution by specific surface area Ds(50) corresponds to 0.2 µm, and the maximum value of the differential coefficient K_{isa} = 168.7 μm^{-1}·vol. % is manifested at 0.17 µm (Fig. 1c). At the same time, the maximum value of the coefficient of surface activity of microsilica exceeds the value of fly ash by 44.2 times, which convincingly indicates a significant effect of the ultrafine fraction of silica fume on the intensification and acceleration of structure-forming processes in cementing systems.



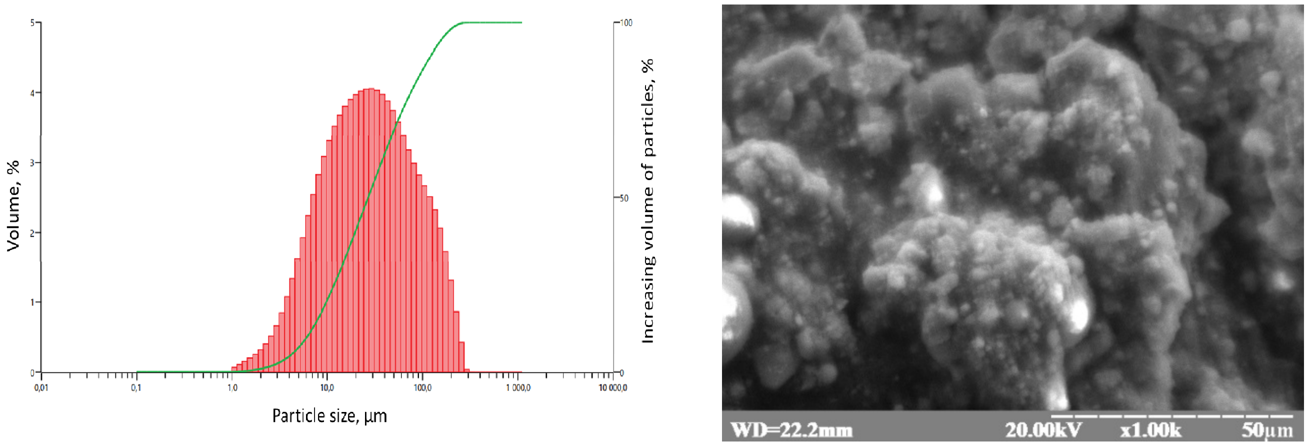
a)

b)

c)

Fig. 1. Differential particle size distribution of fly ash and silica fume by volume (a) and by surface area (b, c)

Taking into account the difference in structural levels of fly ash and microsilica dispersion, a combined pozzolanic additive (CPA) was developed to increase the pozzolanic effect in the cementitious matrix of concrete. The specific surface area of CPA is 5800 cm^2/g. According to laser granulometry data, the content of the fractions Ø5; Ø10; Ø20 µm for CPA is 22.62, 38.01, 59.89 %, respectively, and the grain sizes Dv(10), Dv(50), Dv(90) correspond to 6.08, 27.0, 119 µm. The average diameters D[3; 2] and D[4; 3] are 14.3 and 46.2 µm, respectively. The maximum on the differential distribution curve corresponds to particles with a size of 11.5 µm (Fig. 2a). The combined pozzolanic additive "fly ash – silica fume" is characterized by spherical particles less than 20 µm in size in combination with a fine fraction. It is characteristic that finely dispersed particles of silica fume are attached to the surface of larger ash particles (Fig. 2b).

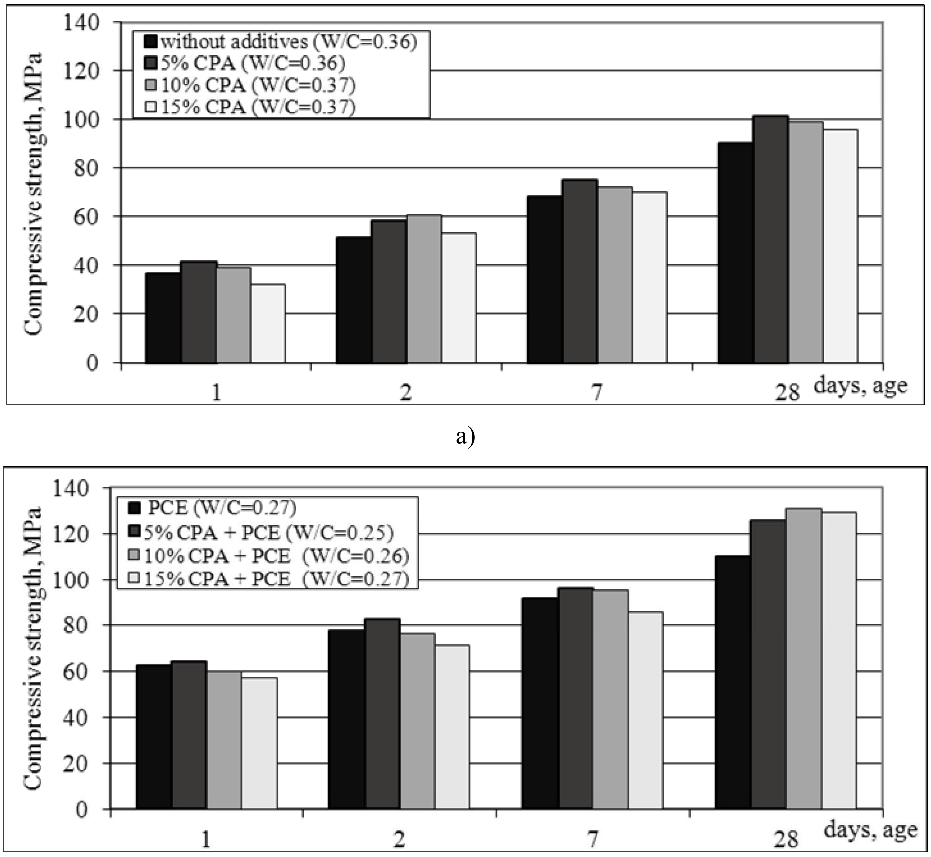


a) b)

Fig. 2. Particle size distribution (a) and micrograph (b) of combined pozzolanic additive

The influence of CPA "fly ash – silica fume" on the physical and mechanical properties of fine-grained concrete (Cement : Sand = 1:1.65) was studied; at the same time, the flowability of the mixture varied within 165-170 mm. It was found that to achieve a desired flowability for the composition without admixture (W/C = 0.34) the strength values after 1, 2, 7, and 28 days were 40.4, 55.6, 72.8, and 103.6 MPa, respectively. When 5.0 wt. % and 10.0 wt. % of CPA were added (W/C = 0.34-0.35), an increase in early strength by 15-16 % was observed after 1 day, by 18-19 % after 2 days and after 28 days the strength values of 107.2 and 113.0 MPa, respectively, were achieved. The introduction of 15 wt.% CPA leads to a slight decrease in the strength of concrete at all curing times – the strength after 1 day was 40.0 MPa, after 2 days – 61.2 MPa, after 7 days – 83.2 MPa, and after 28 days – 112.6 MPa. The physical and mechanical properties of concrete improve when modified with superplasticizer based on polycarboxylate ethers. To achieve the desired mobility, it was found that the introduction of 1.0 wt. % of PCE into the composition of concrete without additives provides a water-reducing effect $\Delta W/C = 26.5$ % and an increase in strength at all curing times. The kinetics of strength gain of the samples with CPA slightly differs from that of samples without PCE. At $\Delta W/C = 30.3$ %, when 5.0 wt. % of CPA and 1.0 wt. % of PCE are added, the strength of the samples increases and amounts to 68.0 MPa after 1 day, 85.6 MPa after 2 days, 98.0 MPa and 125.4 MPa after 7 and 28 days, respectively. At the same time, when 10.0 wt. % of CPA and 1.0 wt. % of PCE are added, a slight slowdown in the kinetics of early strength gain is observed., whereas after 7 and 28 days the strength increases and reaches 100.0 MPa and 130.8 MPa, respectively. The increase in strength values ΔR_{c1}, ΔR_{c7}, and ΔR_{c28} for modified fine-grained concrete is ensured. The highest effect (ΔR_{c1} = 68.3%) after 1 day is observed for modified mixtures containing 5.0 wt. % CPA + 1.0 wt. % PCE, and after 28 days (ΔR_{c28} = 26.9 %) for the mixtures with 10.0 wt. % CPA + 1.0 wt. % PCE, which indicates the high efficiency of the organo-mineral pozzolanic additive "fly ash – silica fume" + PCE.

In the next stage of experiments quartz sand in the composition of fine-grained concrete was replaced by fine polyfractional recycled concrete aggregate. For concrete without additives (Fig. 3a) the strength after 1, 2, 7, and 28 days was found to be 36.8 MPa, 51.3 MPa, 68.5 MPa, and 90.4 MPa, respectively ($W/C = 0.36$). When 5.0 wt. % CPA is added, to achieve flow of 162-165 mm at W/C of 0.36, the concrete strength increases at all curing times by 9-12 % and reaches 45.62 and 109.4 MPa after 1 and 28 days, respectively. An increase in the amount of a highly dispersed pozzolanic additive to 10-15 wt.% slightly increases water consumption (W/C=0.37) and decreases strength at all curing times. At the desired flow of 165 mm, and 1.0 wt.% of PCE in the mixture, we observe $\Delta W/C$=25 % and an increase in strength to 62.5 MPa after 1 day, 77.6 MPa after 2 days, 91.4 MPa after 7 days, and 110.3 MPa after 28 days (Fig. 3b). The introduction of 5.0 wt. % CPA + 1.0 wt. % PCE provides the greatest increase compressive strength (1.7-1.4 times) and in flexure strength (1.4-1.3 times) at all curing times. Thus, the compressive strength after 1 day is 64.1 MPa, 2 days – 82.7 MPa, 7 days – 96.1 MPa and 28 days – 125.7 MPa. At the introduction of 10.0 wt. % CPA + 1.0 wt. % PCE, a slowdown in the kinetics of strength gain is observed. At the same time, the highest strength gain is provided after 1 day (ΔR_{c1} = 74.2 %) and 28 days (ΔR_{c28} = 39.1 %) for modified fine-grained concretes containing 5.0 wt. % CPA + 1.0 wt. % PCE.



a)

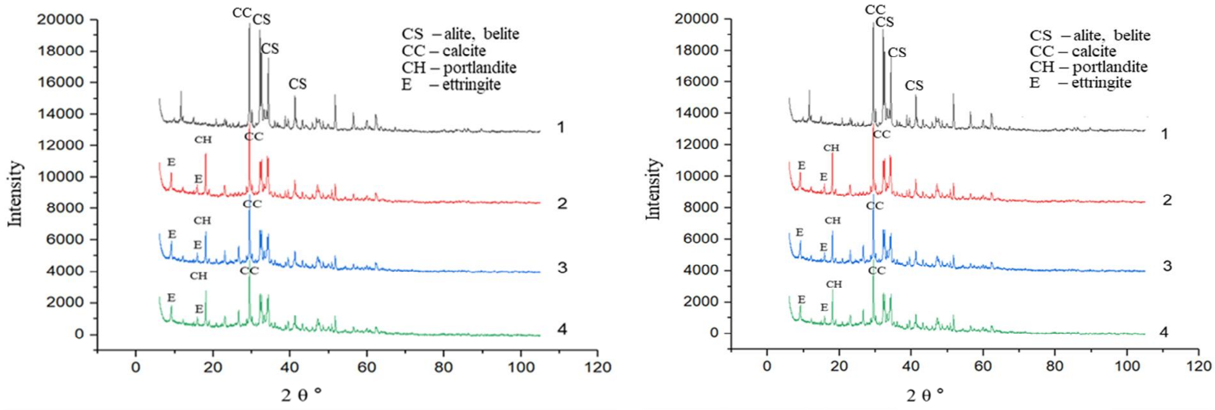
b)

Fig. 3. Compressive strength of fine-grained recycled aggregate concrete without admixture (a) and with PCE (b)

The rheological properties of modified cementing systems (*W*/*C*=0.5) were studied. For Portland limestone cement, the relative viscosity was found to be 3.43 (drain time is 36 s), and the flow according to the Suttard viscosimeter was 190 mm. When adding 5-10 wt. % of CPA to CEM II/A-LL, the relative viscosity of the suspension decreases by 8-10 %. An increase in CPA amount to 20.0 wt. % decreases the relative viscosity by 21.3 %. The introduction of 1.0 wt. % of PCE provides high plasticity of the cementing system, the flow value reaches 260 mm, while the relative viscosity decreases by 1.3 times compared to cement without additives and is equal to 2.52. The introduction of 1.0 wt. % PCE +10 wt. % CPA to the cement results in a sharp decrease in the relative viscosity from 2.52 to 1.43 and an increase in plasticity from 260 to 300 mm. The combination of "fly ash – silica fume" and PCE provides a 1.5-2.0-fold reduction in the relative viscosity and obtaining of a superplasticized cementing system with the Suttard flowability to 310 mm.

For Portland limestone cement CEM II/A-LL, the normal density of cement paste (paste 1:0) is achieved at a water demand of 29.5 %, the initial set is 190 min, and the final set is 260 min. At the same time, the cement paste is characterized by strength values of 38.3, 84.1, and 118.8 MPa after 1, 7, and 28 days of hardening, respectively. With the introduction of 5.0 wt.% of highly active CPA, the normal density is achieved at a water demand of 30 %, and the strength increases at all curing times. With the introduction of 5 wt. % CPA + 1.0 wt. % PCE, to ensure normal density, the water demand decreases to 20.7 %, and the strength increases by 1.64 times (63.0 MPa), 1.3 times (109.7 MPa), and 1.2 times (140.7 MPa) after 1, 7 and 28 days, respectively.

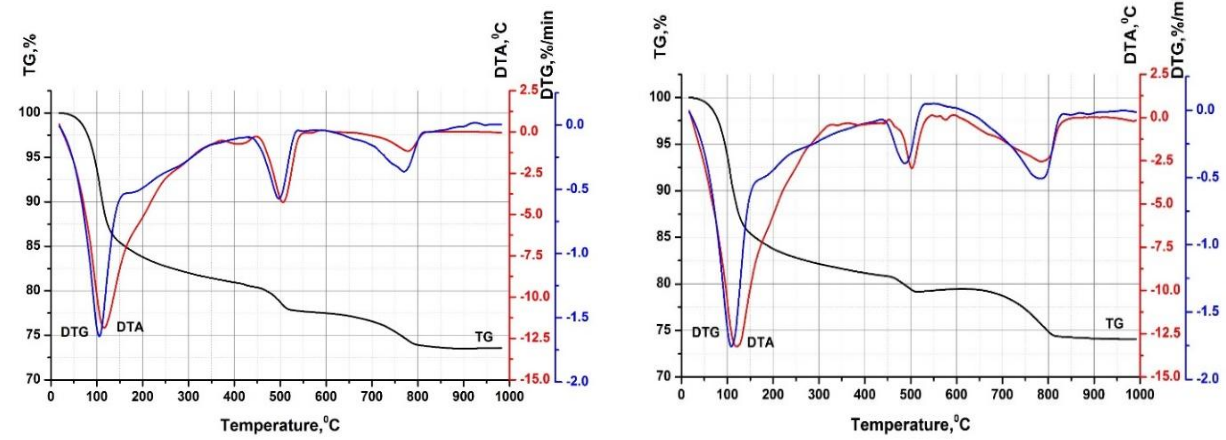
The cement paste samples were examined by X-ray diffraction and their phase composition was determined. The results in the form of a diffractogram are shown in Fig. 4a, b. For cement paste after 24 hours and 28 days of hardening, the lines of calcite (*d*/*n* = 0.303; 0.249 nm), calcium hydroxide (*d*/*n* = 0.490; 0.263 nm), ettringite (*d*/*n* = 0.973; 0.561 nm), *etc*., were recorded. It should be noted that the introduction of 15.0 wt. % of active pozzolanic additive to Portland cement reduces the intensity of calcium hydroxide reflexes by 1.3 times after 24 h, and by 1.5 times after 28 days compared to cement without additives. This indicates that a fine fraction of CPA accelerates the pozzolanization process. The high strength of the modified cement paste is ensured by expanding the effect of ettringite, as well as the formation of low-base calcium hydrosilicates.



a) b)

Fig. 4. Diffractograms of cementitious paste with CPA and PCE additives: after 24 h of hydration (a), and after 28 days of hydration (b); 1 – unhydrated CEM II/A-LL; 2 – hydrated CEM II/A-LL; 3 – hydrated 85.0 wt. % CEM II + 15.0 wt.% CPA; 4 – hydrated 85.0 wt. % CEM II + 15.0 wt. % CPA + PCE

According to the data of quantitative X-ray diffraction analysis by Rietveld, for Portland limestone cement CEM II/A-LL hydrated for 24 h the content of ettringite, portlandite, and X-ray amorphous phase is 12.3 wt. %, 16.2 wt. %, and 43.4 wt. %, respectively. The introduction of 20.0 wt. % CPA results in the increase of ettringite content to 14.7 wt. %, and the content of portlandite decreases to 11.2 wt. %. When CPA is introduced, the reaction surface of Portland cement clinker grains increases due to their expansion. The formation rate of $Ca(OH)_2$, which acts as a CPA activator, also increases, resulting in an incomplete hydrolysis of the vitreous component. The reaction of active Al_2O_3 and $Ca(OH)_2$ contributes to the formation of ettringite. Ettrigite crystals formed at an early stage of cement hydration, provide a crystal skeleton that acts as a reinforcing base for cement paste and contribute to a rapid gain in strength. The introduction of PCE leads to an increase in the amount of the C-S-H phase, while the ettringite and portlandite contents do not change. For the Portland cement paste based on CEM II/A-LL, which was hardened for 28 days, the $Ca(OH)_2$ content is 13.6 wt. %, for the paste with 15.0 wt. % CPA, its content decreases by 1.65 times, for the modified paste with 15.0 wt. % CPA + PCE − by 1.56 times, and the content of the amorphous phase increases from 45.1 wt. % to 49.6 wt. % and 52.7 wt. %. The degree of hydration for cement paste based on 85.0 wt. % CEM II/A-LL 42.5 R + 15.0 wt. % CPA after 24 h and 28 days is 28 % and 78 %, respectively. The introduction of a polycarboxylate superplasticizer leads to a slight slowdown in the early structure formation processes, while the degree of hydration increases after 28 days.



a) b)

Fig. 5. Thermograms of cementitious paste based on CEM II/A-LL (a) and CEM II/A-LL+CPA+PCE (b) hydrated for 24 h

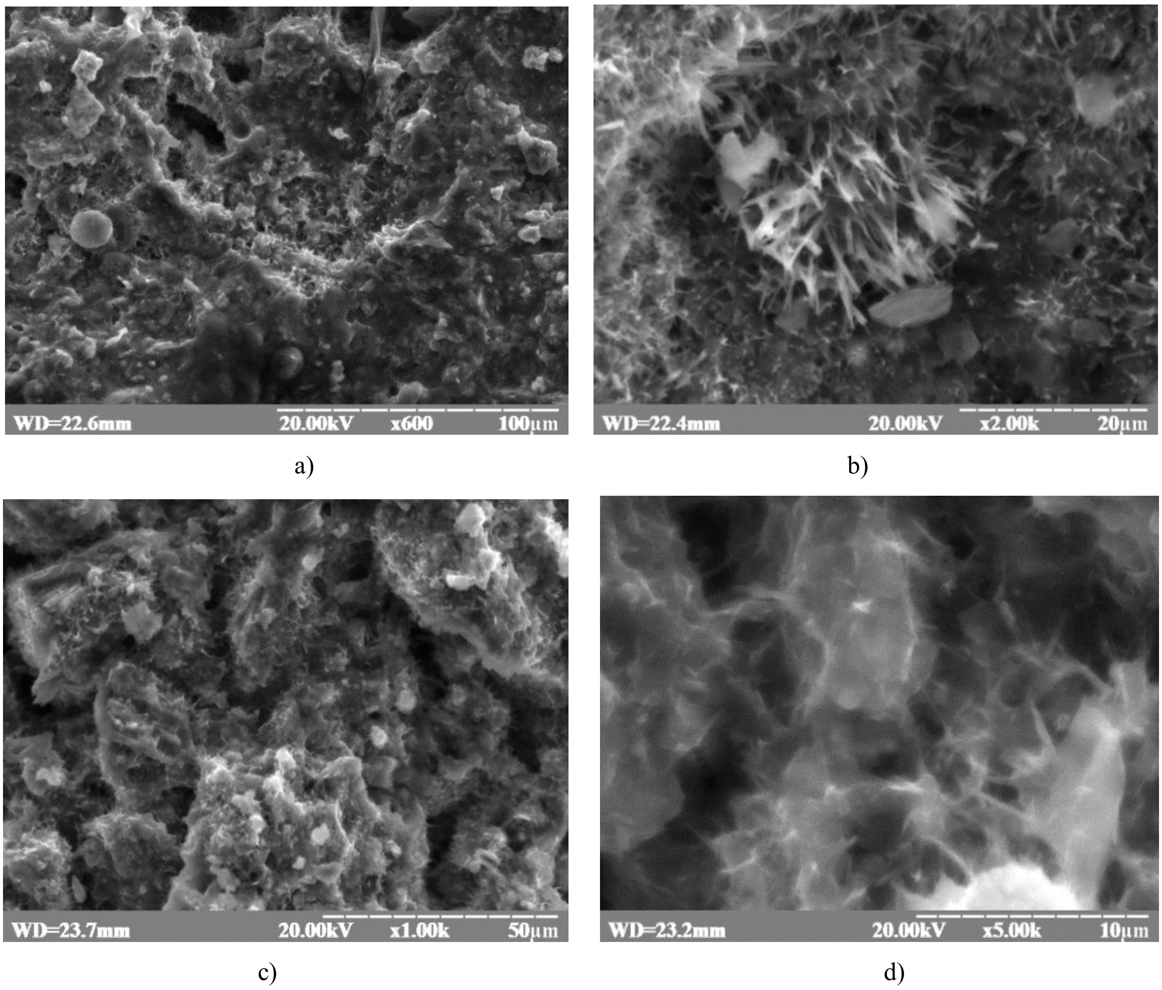


Fig. 6. Microstructure of cementitious paste after 24 h of hydration: CEM II + CPA (a) and CEM II + CPA + PCE (b, c, d)

The results of the thermal analysis of cement paste samples hydrated for 24 h are shown in the form of thermograms (Fig. 5a, b). In the temperature range of 20–165 ºC, the samples lose physically adsorbed moisture; in the same temperature range, partial thermal decomposition of the ettringite occurs.[31] The process is accompanied by a significant weight loss of cement paste samples: Δm = 15.06 % for CEM II/A-LL and Δm = 15.18 % for CEM II/A-LL + CPA + PCE.

An extremum on the DTG curves and a deep endothermic effect on the DTA curves are observed. In the temperature range of 165–438 °C, the stepwise thermal decomposition of ettringite continues and a gradual dehydration of hydroaluminates and hydrosilicates occurs. This process corresponds to a gradual weight loss Δm = 4.41 % for CEM II/A-LL and Δm = 3.92 % for CEM II/A-LL + CPA + PCE. A deviation of DTA curves to the region of endothermic effects is observed. It should be noted that CEM II/A-LL is characterized by a higher content of hydrated phases, as evidenced by a more intense weight loss of this sample. In the temperature range of 438–541 °C for Portland cement paste based on CEM II/A-LL and temperature range of 438–533 °C for CEM II/A-LL+CPA+RCE, dehydration of portlandite occurs. This process is accompanied by a rapid loss of sample weight: Δm = 2.76 % for CEM II/A-LL and Δm = 1.69 % for the CEM II/A-LL + CPA+ PCE system. Characteristically, cement paste based on CEM II/A-LL is characterized by a higher content of $Ca(OH)_2$, the decomposition of which is accompanied by a more intense weight loss of this sample. In the temperature range of 541–670 °C for CEM II/A-LL and range of 533–680 °C for the CEM II/A-LL+CPA+RE system, the dehydration of hydrosilicates is completed, which corresponds to a gradual loss of sample weight: Δm = 1.18 % for CEM II/A-LL and Δm = 1.06 % for CEM II/A-LL+CPA+RCE. A deviation of DTA curves into the region of endothermic effects is observed. At temperatures above 670 °C, thermal dissociation of carbonates occurs. This process is accompanied by a significant loss of sample weight: $\Delta m = 3.07$ % for CEM II/A-LL and $\Delta m = 4.01$ % for the CEM II/A-LL + CPA + PCE system. After 24 h of hardening of the modified cement paste based on CEM II/A-LL + CPA + PCE, the $Ca(OH)_2$ content is 9.2 %, which is 1.6 times less than that of the paste based on CEM II/A-LL.

Micrographs of cement paste samples (water/binder = 0.4) based on CEM II/A-LL + CPA and CEM II/A-LL + CPA + PCE systems after 24 h of hydration are shown in Fig. 6. The results of scanning electron microscopy show that the cementing system of 85 wt. % CEM II/A-LL + 15 wt. % CPA is characterized by a fine crystalline structure, which is manifested in the form of calcium hydrosilicates and plate-shaped individual crystals of portlandite (Fig. 6a, b).

At the introduction of 1.0 wt. % of PCE, the friable structure of the modified cement paste is revealed due to the increased amount of water. By influencing the processes of structure formation, especially at the initial, coagulation stage, PCE changes the rheological properties of the cementing system and contributes to a reduction in its water demand, which is further reflected in the properties of the crystallization structure. Fig. 6c, d shows that the introduction of PCE promotes the formation of an additional amount of C-S-H-gel, which increases the volume of internal hydrate formations – a significant amount of finely dispersed calcium hydrosilicates is observed on the surface of the grains. The combination of fly ash and silica fume in CPA can eliminate some of the disadvantages of pozzolans − accelerate the pozzolanic reaction during cement hydration, and compact the structure at the meso- and microlevels of the cementitious matrix of the concrete.

Thus, the use of Portland limestone cement, active pozzolanic additives (fly ash, silica fume), and their combination with polycarboxylate superplasticizers provides modification of the mesostructure of fine-grained concrete with recycled aggregate and creates the possibility of achieving high workability and strength. Multicomponent SCMs fill cement paste voids and contribute to the compactness of the ITZ structure by reacting with calcium hydroxide to form C-S-H-gels, which in turn improve the macroscopic characteristics of RAC. The implementation of SCMs and silica fume in combination with 100 % recycled concrete aggregates resulted in a 41 % reduction in CO_2 emissions, as well as an increase in a number of durability indicators.[32] Therefore, establishing the influence of active pozzolanic additives, such as fly ash and silica fume, on the technical properties of RAC is important in the context of reducing the carbon footprint in construction production.

4. Conclusions

The synergistic combination of pozzolanic additives of the micro- and ultradispersity level of the "fly ash-silica fume" system in a complex with polycarboxylate superplasticizers allows you to regulate the rheological properties of Portland cements and optimize the performance of the cementitious matrix to ensure its high density. At the same time, there is also a simultaneous increase in strength and a decrease in the porosity of the interfacial transition zone of RAC, which is a critical factor that determines the durability of concrete structures.

The use of recycled aggregate concrete not only reduces the consumption of natural materials but also helps to reduce CO_2 emissions. Further study of the effects of SCMs and modifiers to improve the ITZ structure of RAC has important practical implications. Complete concrete recycling can be scaled up and deployed on an industrial scale, thus contributing to the carbon-neutral concrete of the future.

References

[1] UN Environment; Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-Efficient Cements: Potential Economically Viable Solutions for a low-CO_2 Cement-Based Materials Industry. *Cem. Concr. Res.* **2018**, *114*, 2–26. http://dx.doi.org/10.1016/j.cemconres.2018.03.015

[2] Pizoń, J.; Gołaszewski, J.; Alwaeli, M.; Szwan, P. Properties of Concrete with Recycled Concrete Aggregate Containing Metallurgical Sludge Waste. *Materials* **2020**, *13*, 1448. https://doi.org/10.3390/ma13061448

[3] González, M.; Caballero, P.; Fernández, D.; Vidal, M.; Bosque, I.; Martínez, C. The Design and Development of Recycled Concretes in a Circular Economy Using Mixed Construction and Demolition Waste. *Materials* **2021**, *14*, 4762. https://doi.org/10.3390/ma14164762

[4] Evangelista, L.; Brito, J. Durability Performance of Concrete Made with fine Recycled Concrete Aggregates. *Cem. Concr. Compos*. **2010**, *32*, 9–14. https://doi:10.1016/j.cemconcomp.2009.09.005

[5] Pacheco, J.; Brito, J. Recycled Aggregates Produced from Construction and Demolition Waste for Structural Concrete: Constituents, Properties and Production. *Materials* **2021**, *14*, 5748. https://doi.org/10.3390/ma14195748

[6] Tošić, N.; Torrenti, J. New Eurocode Provisions for Recycled Aggregate Concrete and their Implications for the Design of One-Way Slabs. *Build. Mater. Struct.* **2021**, *64*, 119–125. https://doi.org/10.5937/GRMK2102119T

[7] Troian, V.; Gots, V; Keita, E.; Roussel, N.; Angst, U.; Robert, J. Challenges in Material Recycling for Postwar Reconstruction. *Techn. Lett.* **2022**, *7*, 139–149. https://doi.org/10.21809/rilemtechlett.2022.171

[8] Xie, T.; Gholampour, A.; Ozbakkaloglu, T. Toward the Development of Sustainable Concretes with Recycled Concrete Aggregates: Comprehensive Review of Studies on Mechanical Properties. *J. Mater. Civ. Eng.* **2018**, *30*, 04018211. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002304

[9] Akhtar, A.; Sarmah, A.K. Construction and Demolition Waste Generation and Properties of Recycled Aggregate Concrete: A Global Perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. https://doi.org/10.1016/j.jclepro.2018.03.085

[10] Fawzy, A.; Elshami, A.; Ahmad, S. Investigating the Effects of Recycled Aggregate and Mineral Admixtures on the Mechanical Properties and Performance of Concrete. *Materials* **2023**, *16*, 5134. https://doi.org/10.3390/ma16145134

[11] Kroviakov, S.; Volchuk, V.; Zavoloka, M.; Krizhanovsky, V. Search for Ranking Approaches of Expanded Clay Concrete Quality Criteria. *Mater. Sci. Forum* **2019**, *968*, 20–25. https://doi.org/10.4028/www.scientific.net/MSF.968.20

[12] Juenger, M.C.; Snellings, R.; Bernal, S. A. Supplementary Cementitious Materials: New Sources, Characterization, and Performance Insights. *Cem. Concr. Res.* **2019**, *122*, 257–273. https://doi.org/10.1016/j.cemconres.2019.05.008

[13] Sanytsky, M.; Rusyn, B.; Kirakevych, I.; Kaminskyy, A. Architectural Self-Compacting Concrete Based on Nano-Modified Cementitious Systems. In *Proceedings of CEE 2023. Lecture Notes in Civil Engineering*, vol 438; Blikharskyy, Z.; Koszelnik, P.; Lichołai, L.; Nazarko, P.; Katunský, D., Eds; Springer, Cham., 2024; pp 372–380. https://doi.org/10.1007/978-3-031-44955-0_37

[14] Sikora, P.; Lootens, D.; Liard, M.; Stephan, D. The Efects of Seawater and Nanosilica on the Performance of Blended Cements and Composites. *Appl. Nanosci.* **2020**, *10*, 5009–5026. https://doi.org/10.1007/s13204-020-01328-8

[15] Giergiczny, Z. Fly Ash and Slag. *Cem. Concr. Res.* **2019**, *124*, 105826. https://doi.org/10.1016/j.cemconres.2019.105826

[16] Chandra, L.; Hardjito, D. The Impact of Using Fly Ash, Silica Fume and Calcium Carbonate on the Workability and Compressive Strength of Mortar. *Proc. Eng.* **2015**, *125*, 773–779. https://doi.org/10.1016/j.proeng.2015.11.132

[17] Krivenko, P.; Runova, R.; Rudenko, I. Analysis of Plasticizer Effectiveness During Alkaline Cement Structure Formation. *East.-Eur. J. Enterp. Technol.* **2017**, *4(6(88)*, 35–41. https://doi.org/10.15587/1729-4061.2017.106803

[18] Matias, D.; Brito, De J.; Rosa, A.; Pedro D. Mechanical Properties of Concrete Produced with Recycled Coarse Aggregates–Influence of the Use of Superplasticizers. *Const. Build. Mat.* **2013**, *44*, 101–109. https://doi.org/10.1016/j.conbuildmat.2013.03.011

[19] Junak, J.; Sicakova, A. Effect of Surface Modifications of Recycled Concrete Aggregate on Concrete Properties. *Buildings* **2018**, *8*, 2. https://doi.org/10.3390/buildings8010002

[20] Sanytsky, M.; Kropyvnytska, T.; Fischer, H.-B.; Kondratieva, N. Performance of Low Carbon Modified Composite Gypsum Binders with Increased Water Resistance. *Chem. Chem. Technol.* **2019**, *4*, 495–502. https://doi.org/10.23939/chcht13.04.495

[21] Sanytsky, M.; Kropyvnytska, T.; Ivashchyshyn, H. Sustainable Modified Pozzolanic Supplementary Cementitious Materials Based on Natural Zeolite, Fly Ash and Silica Fume. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1254*, 012004. https://doi.org/10.1088/1755-1315/1254/1/012004

[22] Singh P. Study the Effect of Fly Ash, Silica Fume and Recycled Aggregate on the Compressive Strength of Concrete. *Int. J. Res. Eng. Adv. Techn.* **2015**, *3*, 71–78. https://www.academia.edu/36958214

[23] Bedoya, M.A.; Tobón, J.I. Incidence of Recycled Aggregates and Ternary Cements on the Compressive Strength and Durability of Ecological Mortars. *Case Stud. Constr. Mat.* **2022**, *17*, 01192. https://doi.org/10.1016/j.cscm.2022.e01192

[24] Su, Y.; Yao,Y.; Wang, Y.; Zhao, X.; Li, L.; Zhang, J. Modification of Recycled Concrete Aggregate and Its Use in Concrete: An Overview of Research Progress. *Materials* **2023**, *16*, 7144. https://doi.org/10.3390/ma16227144

[25] Sun, Zh.; Xiong, J.; Cao, Sh.; Zhu, J.; Jia, X.; Hu, Z.; Liu, K. Effect of Different Fine Aggregate Characteristics on Fracture Toughness and Microstructure of Sand Concrete. *Materials* **2023**, *16*, 2080. https://doi.org/10.3390/ma16052080

[26] Krivenko, P.; Kovalchuk, O.; Boiko, O. Practical Experience of Construction of Concrete Pavement Using Non-Conditional AGGREGATES. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *708*, 012089. https://doi.org/10.1088/1757-899X/708/1/012089

[27] Pushkarova, K.; Kaverin, K.; Kalantaevsky, D. Research of High–Strength Cement Compositions Modified by Complex Organic–Silica Additives. *East.-Eur. J. Enterp. Technol.* **2015**, *5(5(77)*, 42–51. https://doi.org/10.15587/1729-4061.2015.51836

[28] Mironyuk, I.; Tatarchuk, T.; Paliychuk, N.; Heviuk, I.; Horpynko, A.; Yarema, O.; Mykytyn, I. Effect of Surface-Modified Fly Ash on Compressive Strength of Cement Mortar. *Mater. Tod. Proc.* **2021**, *35*, 534-537. https://doi.org/10.1016/j.matpr.2019.10.016

[29] Sanytsky, M.; Usherov-Marshak, A.; Kropyvnytska, T.; Heviuk, I. Performance of Multicomponent Portland Cements Containing Granulated Blast Furnace Slag, Zeolite, and Limestone. *Cement Wapno Beton* **2020**, *5*, 416–427. https://doi.org/10.32047/CWB.2020.25.5.7

[30] Sanytsky, M.; Kropyvnytska, T.; Shyiko, O. Effect of Potassium Sulfate on the Portland Cement Pastes Setting Behavior. *Chem. Chem. Technol.* **2023**, *17,* 170–178. https://doi.org/10.23939/chcht17.01.170

[31] Kochubei, V.; Yaholnyk, S.; Bets, M.; Malovanyy, M. Use of Activated Clinoptilolite for Direct Dye-Contained Wastewater Treatment. *Chem. Chem. Technol.* **2020**, *14*, 386–393. https://doi.org/10.23939/chcht14.03.386

[32] Jiménez, L.F.; Domínguez, J.A.; Vega-Azamar, R.E. Carbon Footprint of Recycled Aggregate Concrete. *Adv. Civ. Eng.* **2018**, *2018*, 949741. https://doi.org/10.1155/2018/7949741

[33] DSTU B V.2.7-187:2009. Building materials. Cements. Methods of determination of bending and compression strength; Ukrarkhbudinform: Kyiv, Ukraine, 2010.

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ВПЛИВ ПУЦОЛАНОВИХ ДОБАВОК НА ВЛАСТИВОСТІ ЦЕМЕНТУЮЧОЇ МАТРИЦІ БЕТОНІВ З ЗАПОВНЮВАЧАМИ РЕЦИКЛІНГУ

Анотація. *У статті описано вплив пуцоланових добавок і полікарбоксилатного суперпластифікатора на характеристики цементуючої матриці бетону із заповнювачем рециклінгу. Наведено гранулометричний склад за об'ємом і площею поверхні для золи-винесення та кремнеземного пилу, досліджено фазовий склад і мікроструктуру цементного каменю.*

Ключові слова: *зола-винесення, мікрокремнезем, заповнювач рециклінгу, полікарбоксилатний суперпластифікатор, цементуюча матриця, бетон.*