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Influence of Porous Aggregate on the Properties of Foamed Concrete

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***Abstract* – Nowadays energy-efficient use of building resources is getting more and more popular. Technological developments have promoted production of new building materials with improved physical, mechanical and thermal properties. Foamed concrete with porous aggregate can serve as an alternative material for the existing lightweight concrete materials. This building material shows good mechanical and thermal properties, as well as capillary absorption and shrinkage test results that attest the longevity of this building material.**

***Keywords* – Capillary absorption, ceramsite, expanded glass, porous aggregate, shrinkage.**

I. Introduction

Beginning of aerated concrete (AC) dates back to the first half of the 20th century, when in 1911 a Danish engineer, Bayer, for the first time offered a mix of mineral components with foam, creating foamed concrete [1]. Wider industrial production of foamed concrete (FC) began in the 1930ies in Germany, Denmark, and Russia, when several factories, where aerated concrete was hardened in autoclaves, were built. Later, in the 1950ies production of aerated concrete by the Swedish technology "Siporex" rapidly developed. Regeneration of FC began with production of efficient synthetic foaming additives and the introduction of tighter margins in building envelope [2].

FC, like aerated concrete, belongs to the group of porous (also called cellular) concretes. This material combines satisfactory physical and mechanical (such as density, compressive strength) and thermal properties. FC can be classified by its use: constructive, constructive – insulating and lightweight foamed concrete.

Each type of FC is characterized by different physical, mechanical and thermal performance characteristics, which are listed in Table I.

TABLE I
Classification of Foamed Concrete, the Main Characteristics

Type of foamed concrete	Density, kg/m³	Compressive strength, MPa	Thermal conductivity coefficient, W/mK
Constructive foamed concrete	600 – 2000	6 – 60	0.15 – 1.0
Constructive insulating foamed concrete	350 – 600	1 – 6	0.1 – 0.20
Ultra lightweight concrete	<350	0.1 – 2	0.04 – 0.15

Technology of FC production is simpler and more flexible comparing to production of silicate autoclaved aerated concrete (AAC). Production process of FC includes preparation of a mixture of foam and cement mortar and hardening under normal circumstances, as in the case of traditional concrete. A classification of cellular concretes is demonstrated in Fig. 1. Calcium hydroxide (the product of reaction between cement and water) reacts with aluminium powder, causing formation of microscopic air bubbles or pores, which results in extraction of autoclaved cellular concrete structure (AAC). Porous structure of FC is obtained by physical – mechanical methods, using natural or synthetic air – entraining admixture called foaming agents.

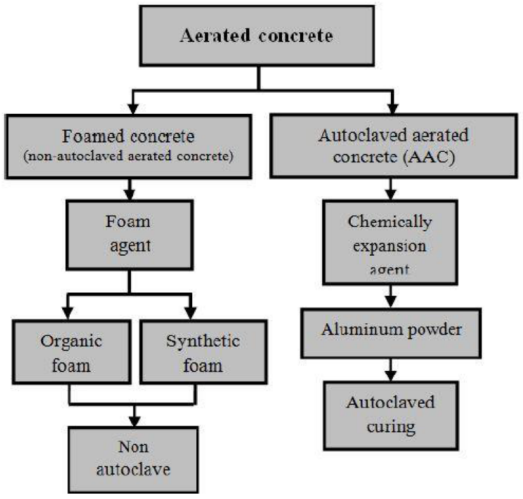

Fig. 1. Classification of cellular concrete by producing technologies [3].

Use of FC has many significant advantages, e.g. fast producing process. Secondly, it is easy to work with FC (simple constructive solutions can be found, it is also easy to saw and screw FC). This material demonstrates excellent heat insulation properties, thus helps save energy resources, and that currently is a significant factor. Productivity of working with FC is not less important. Its use on the construction site (in structures) allows both increasing productivity and reducing the cost of construction works. Use of FC allows reducing the product mass from 10 % to 85 %, compared to a traditional concrete. It depends on the components of the mixture used and their proportions. [4].

Like any material, FC has its own drawbacks. One of the major disadvantages is the process of drying shrinkage (compared to a traditional concrete, it is greater). Also, there is a risk that the drying cracks appear [5]. Lower strength values at the same density as compared to the AAC are another significant disadvantage of FC. It can be concluded that the production technology of foamed concrete plays an important role.

Technologies should be developed in order to achieve the best ratio between the mechanical strength and density of the building material. This would provide greater strength at the same density or even reduced density at the same strength.

In order to ensure the competitiveness of FC, it is necessary to use modern preparation technologies and methods. This should be settled in two main directions: first, composing a mixture of active additives such as pozzolanic microsilica, metakaolin or substances with nano particles. Second, it is necessary to use an innovative mixing technology with cavitation and turbulence effects that would ensure production of the homogeneous mixture, thus improving the properties of FC. Adding porous aggregate (such as granules of ceramsite or expanded glass) to the concrete mixture composition can serve as an alternative solution for improving the properties of FC.

A. Shrinkage

Shrinkage (decrease of the volume over time in the curing process) of FC is considered one of the main disadvantages. Comparing to AAC, FC has a greater shrinkage deformation rate. Shrinkage of cellular concrete (including FC) depends on several factors: the method of preparation, used components and their characteristics (whether special additives or fillers are added, their amount), density of concrete, the amount of water in the mixture, duration of climate exposure and storage, the pore structure and its distribution, etc.[6], [7].

B. Types of Shrinkage

Decrease of humidity level in FC and physical-chemical changes are considered the main reasons of shrinkage. These include the main types of shrinkage deformation: drying shrinkage (depending on water migration through the FC during the time of hardening) and autogenous shrinkage (due to chemical processes, it begins to develop in the first few days after concreting) [8], [9]. As a result of drying shrinkage and humidity changes, the process of weight changes (losses) also takes place in FC. With excessive drying shrinkage rate, the cracks begin to form in the material , altering its uniformity and having a negative effect on the strength and durability [10].

Carbonation is referred to as another type of shrinkage. It runs in FC during or after the process of hardening as a chemical reaction (in the presence of moisture), but it does not make significant changes in the volume of FC [6].

Carbonation is a long – lasting process and it starts from the surface of FC. Compared to traditional concrete, the depth of carbonation of FC is much higher. It can be explained by larger number of pores in the structure of FC. As a result, infiltration of carbon dioxide is higher. An alkaline reaction medium that protects the steel reinforcement from carbonisation is reduced by formation of calcium carbonate. But for FC this disadvantage is not as significant as for traditional constructive concrete, as in FC coated steel, glass, composite fibers, etc. are used. However, carbonation and drying shrinkage processes combine and can cause deformations and cracks, which leave a significant impression on the durability properties of FC [6], [11].

C. Opportunity to Reduce the Process of Shrinkage

Modern studies have shown that shrinkage of FC can be reduced by using extra additives and light, porous aggregates. For example, it is proved in [11], [7] that adding manufacturing products such as fly ash, drying shrinkage rates will be lower (comparing to the same mixture of FC without these micro additives. The use of fly ash provides a compact microstructure of the mixture and reduces pore size. Adding polypropylene fibers to the mixture of FC reduces the number of micro cracks (according to study results [11]).

Addition of various porous aggregates has been widely studied [12], [13], [14]. The use of porous aggregates makes it possible to reduce shrinkage of FC [6]. Porous and lightweight aggregates act as internal water reservoirs, supplying additional water through the concrete mixture and providing curing process of FC from inside (the method known as internal curing). As a result, it encourages more complete cement hydration process. This method is particularly beneficial in concrete with a low water /cement ratio with low permeability [8]. The principle of internal curing is shown in Fig. 2.

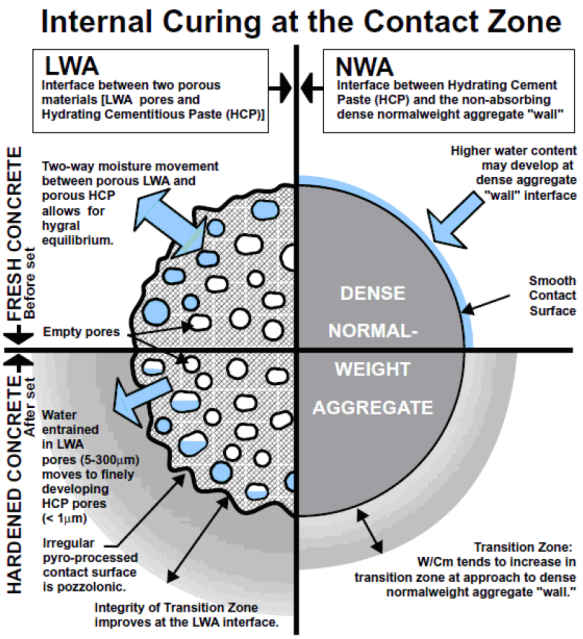

Fig. 2. Curing process of concrete from inside out (internal curing), using light, porous aggregates [15].

Comparing normal weight aggregate to light and porous aggregate, it is evident that the porous filling material has several advantages in mitigation of shrinkage. To ensure moisture balance, water migration takes place through the pore structures of aggregates and hydrated cement paste. Water, which is drawn into the largest pores of aggregate, later in the process of hardening moves to the pores of the cement matrix. Consequently, FCs containing porous aggregates is unable to dry out so fast, shrinkage deformation is reduced and they are protected from excessive cracking at an early age [12].

II. Materials

In this experimental study ordinary Portland cement (PC) CEM I 42.5N (according to requirements of LVS EN 197 – 1:2011) was used. Compressive strength of PC after 2 days was 26 MPa, after 28 days – 58 MPa; the specific surface of PC – 3,600 cm^2/g (produced by "Kunda Nordic Tsement", Estonia).

Natural, dried sand (fraction 0/1 mm) was used as filler. In this case sand has two functions; it is used as filler and it promotes the rise of foam in the mixture of FC.

In this study synthetic foam agent was used as surfactant. It was added in the process of mixing, before that foam agent was mixed with water.

Microsilica (MS) and metakaolin (MK) were used as pozzolanic additives. For the mixtures of FC the MS 971U with bulk density 250 – 350 kg/m^3 produced by "Elkem" was added. MS has fine, spherical shape particles with an average diameter 0.10 μm, that is about 100 times smaller than average PC particles [16]. It helps reduce free space between particles in the cement matrix; as a result, the packing of additives is improved. MS is a pozzolanic additive, because of the reaction between amorphous silicon dioxide and calcium hydroxide; a byproduct of cement hydration, additional cementitious effect is obtained. Including MS in the concrete mixture, the content of SiO_2 increases, strength, durability and the specific surface area of concrete increase (the binding capacity of concrete improves) [17]. Mineral pozzolanic additive – metakaolin-based waste (MK) – is a technogenic waste, obtained as a fine powder during the manufacturing process of expanded glass granules (in JSC "Stikloporas", Lithuania). Bulk density of MK ranges from 0.4 to 0.7 g/cm^3. MK helps improve the strength and workability properties of concrete, the durability against aggressive environment also increases because of the reduction of permeability[18]. At the same time, pozzolanic admixtures help decrease the risk of algally – silica reactions, which may take place between Portland cement and glass aggregate.

For the preparation of FC mixes, expanded glass granules (EG) produced by JSC "Stikloporas" were used as one of the shrinkage reducing porous aggregates. EG granules with fraction 4 to 8 mm (white – cream colored) (see Fig. 3) and smaller fraction – 2 to 4 mm (grey colored) were used.

Recycled glass is used in the manufacturing process of granulated EG. When recycled glass is milled, mixed with blowing agents and melted down at extremely high temperature, the porous structure of the aggregate forms. EG granules are incombustible material with chemical and biological persistence. Granules are not subjected to the processes of decompose or decay; they do not attract rodents and other vermin [19].

Thanks to the closed cavities inside the pore structure of EG granules (see Fig. 4), they have some other advantages. Granulated foam glass is a durable material and remains unchanged for many years. Closed – pore structure provides good thermal and sound insulation properties and low water absorption ability [19].

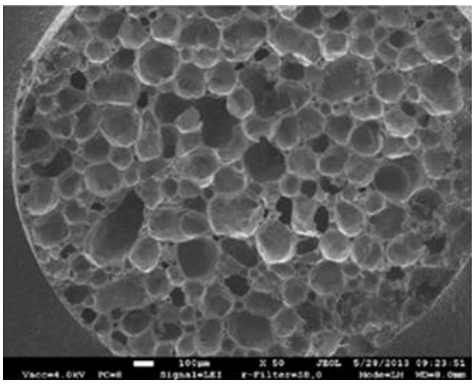

Fig. 4. Internal view of expanded glass granule (fraction 2 to 4 mm), magnification of 50 times [19].

Technical parameters of granulated EG used in this study according to data of producer JSC "Stikloporas" are summarized in Table II.

Another porous aggregate used in this study was granules of ceramsite with fraction size 2 to 8 mm and bulk density 450 kg/m^3 obtained in concrete production plant "Buvema" BBR, Latvia. Granules of ceramsite are a material with good mechanical resistance (range of compressive strength 0.3 – 5.5 MPa), chemical and biological persistence.

Polypropylene fibers (PP) were used in this study as well. When added to FC mixture, PP fibers do not provide a huge improvement of physical and mechanical properties of FC (because of the low modulus of elasticity: 3500 – 8000 MPa). However, by making up and structuring the material of FC, PP fibers increase the deformation till collapse of FC [20].

Superplastifying chemical concrete admixture based on polycarboxylate and produced by "Stachema" was also used.

Fig. 3. Expanded glass granules (white – cream colored), fraction 4 to 8 mm (ruler units in cm).

TABLE II

Technical Data of Expanded Glass Granules

Characteristics	White – cream colored EG granules, fraction 4 to 8 mm	Grey colored EG granules, fraction 2 to 4 mm
Bulk density, kg/m^3	190	200
Compressive strength, MPa	1.2	1.4
Thermal conductivity, W/mK	0.0631	0.0691
Water absorption, by mass, % (after 24 hours soaking in water)	20	23

III. Methods of Testing

A. Prepared Compositions of Foamed Concrete Mixtures

Three mixtures of FC were prepared in this study. The first one (IV) – control or reference mixture, it was prepared without porous aggregate. For the second mixture (IV K), granulated ceramsite was used as porous aggregate, but for the preparation of the third mixture (IV P) – expanded glass granules (two different colors and fractions). Compositions of the prepared mixtures are summarized in Table III.

TABLE III
Composition of Experimental Mixtures
(Weight Proportions of the Cement)

Used materials	Designation of FC mixtures		
	IV	IV K	IV P
Portland cement CEM I 42.5 N	1.00	1.00	1.00
Sand 0/1 mm	0.57	0.57	0.57
Water	0.64	0.64	0.64
Synthetic foam agent	0.006	0.006	0.006
Metakaolin	0.07	0.07	0.07
Microsilica "Elkem" 971U	0.04	0.04	0.04
EG granules 2/4 mm (grey colored)	–	–	0.54
EG granules 4/8 mm (white – cream colored)	–	–	0.63
Granulated ceramsite 2/8 mm	–	1.87	–
PP fibers	0.004	0.004	0.004
Superplasticizer	0.011	0.011	0.011
Water/cement ratio	0.64	0.64	0.64

B. Density

Density test was performed for specimens of regular size (100 mm × 100 mm × 100 mm), when their weight and geometry were determined, according to requirements of LVS EN 12390-7. For determination of density (kg/m^3) the following formula was used:

$$\rho_o = m_1/V_1 \quad (1)$$

where:
m_1 – mass of the specimen (kg);
V_1 – volume of the specimen (including pores and voids of the specimen) (m^3).

Geometrical dimensions of FC cubes were measured by sliding caliper "Topex" with the range 150 mm and measurement accuracy ±0.05 mm. The weight of the specimens was determined using balance "KERN KB" with maximum weighing range 10100 g and accuracy ±0.1 g.

C. Compressive Strength

Compressive test for specimens with standard dimensions (100 mm × 100 mm × 100 mm) was performed according to LVS EN 771 – 3 after 7 and 28 days of hardening (samples were stored at the temperature 15 – 20 °C and relative humidity >90 %).

Specimens were tested using semi – automatic compression testing machine "CONTROLS" (see Fig. 5). The load during the test was applied at a constant rate (~0.05 MPa/s).

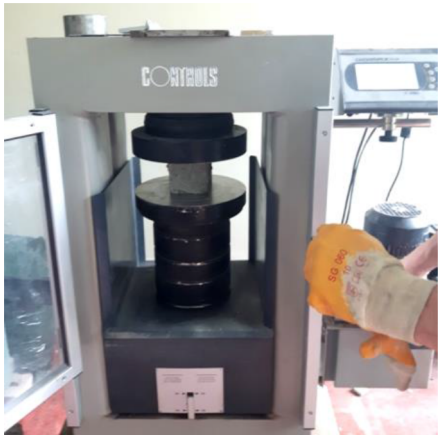

Fig. 5. Foamed concrete sample prepared for the compression test in a compression testing machine.

D. Capillary Water Absorption

Test of capillary water absorption was done using the methodology according to LVS EN 772 – 11. The specimens with the size 100 mm × 100 mm × 100 mm were immersed in water to a depth of 5±1 mm (see Fig. 6). Supports under the specimens were used to ensure the constant water level for the specimens.

Before testing, dry samples were weighted to determine their initial weights. After the immersion time (after 10, 15, 20, 30 minutes, then after 1, 1.5, 2, 3, 6, 24 hours from the start of this test) specimens were removed from water and weighted again.

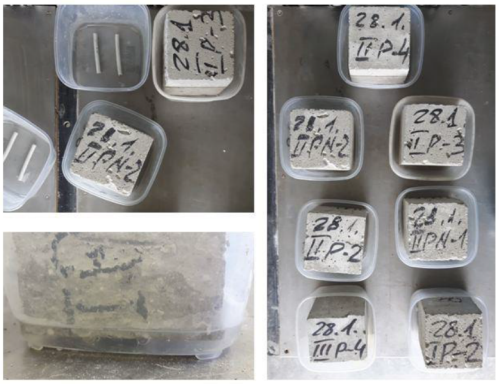

Fig. 6. Some of the samples of capillary water absorption test.

At first, the process of weighing was managed in shorter periods of time, as water in capillary pores of foamed concrete got in faster, later the process occurred slower. The values of coefficient of capillary water absorption C (g/dm^2) were calculated by formula:

$$C = (m_s - m_{dry})/A_s \quad (2)$$

where:
m_s – mass of the specimen after soaking (g);
m_{dry} – mass of the specimen after drying (g);
A_s – the cross area of the face of the specimen immersed in water (dm^2).

E. Characterization of Structure

To characterize location of porous aggregate in the matrix of composite FC, the specimens were sawn in half. Fig. 7 presents the equable layout of granulated foam glass and ceramsite through the cross – section of the specimens. Granules are not concentrated in separate parts of cross – section.

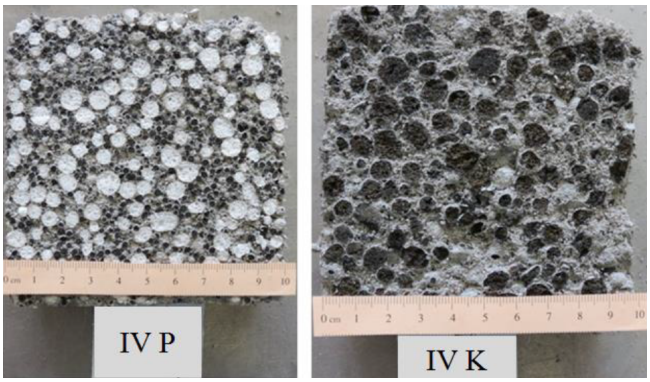

Fig. 7. Cross – sections of the specimens from IV P (with EG granules) and IVK (with granules of ceramsite) mixtures.

In practice there are cases when porous aggregate used for the preparation of FC mixture is too light. This is why granules of ceramsite are located at the upper part of the cross – section of specimen; granules are floating in the matrix of FC (see Fig. 8). The test sample was prepared in 2013.

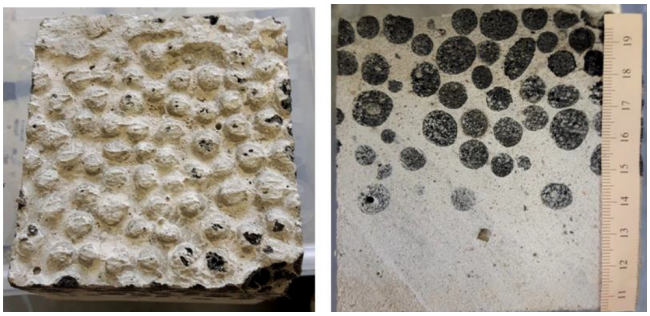

Fig. 8. Test sample of FC with granulated ceramsite (with uneven layout of the aggregate).

It can be explained by the difference between density of the used aggregate and FC matrix. In this case (see Fig. 8), density of granules of ceramsite is much less than the density of FC without porous aggregate. Because of the uneven location of the aggregate and its concentration at the upper part of FC, the use of that kind FC is limited. The surface of FC is very rough and rugged; the center of gravity has shifted as well.

F. Shrinkage

Shrinkage test was performed according to ASTM C490/490M–11. Special molds for the preparation of the prismatic specimens were used (see Fig. 9); at the end of the molds there was a space for screws worked in the specimens (head of the screw is inside the sample and stem outside). Screws are necessary to place the specimens in the length change measuring instrument where the principal axes of the gauge studs coincided with the principal exes of tested specimens.

Fig. 9. Molds used in the process of preparing prismatic FC samples.

For determination the length change, FC prisms with dimensions 25 mm × 25 mm × 285 mm were used (see Fig. 10). Diameter of the stem of screw was 6 mm. Before specimens were placed in the length measuring instrument, a steel reference bar with length of 295 ± 3.0 mm and diameter of 6 ± 0.25 mm was placed in the instrument. Each time when readings were taken, the reference bar and the specimens in the measuring instrument were placed with the same orientation to minimize changes in reading. Till 28 days of hardening, prepared specimens were stored at the temperature 22 °C and relative humidity ~90 %, but later the relative humidity reduced (<90 %).

Fig. 10. Some of the samples prepared for the shrinkage test.

IV. Results and Discussions

A. Compressive Strength and Density

The results of compressive test (after 7 and 28 days of curing) are summarized in the diagram (see Fig. 11).

Analyzing the data of compressive strength test, it can be deduced that higher values of compressive strength (both 7 and 28 days after hardening) were obtained by those mixtures of FC where porous aggregate was not included. It can be explained by

lower porosity and denser structure of the specimens, comparing to the mixtures with the porous aggregate included.

For example, density of mixture IV P is 376 kg/m^3 and compressive strength (28 d) – 1.8 MPa, while density of mixture IV is 581 kg/m^3 and the value of compressive strength (28 d) obtained is about 33 % higher (2.4 MPa).

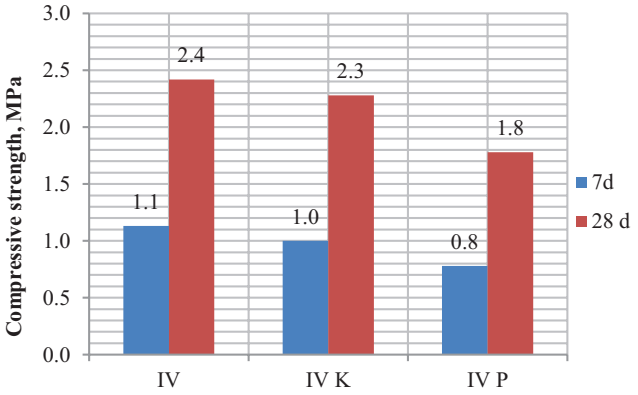

Fig. 11. Compressive strength test results.

B. Capillary Water Absorption

Data obtained from the capillary water absorption test (time period of the first 3 hours) are summarized in a graph (see Fig. 12).

Research results of capillary action of composite FC showed that the mixtures prepared using light and porous aggregate have lower values of the coefficient of capillary water absorption. Although the density of these mixtures was lower (accordingly, their structure was more porous), capillary transport in these specimens was not very intensive. It can be explained by water absorption properties of the used porous aggregate (their ability of water absorption is not very high).

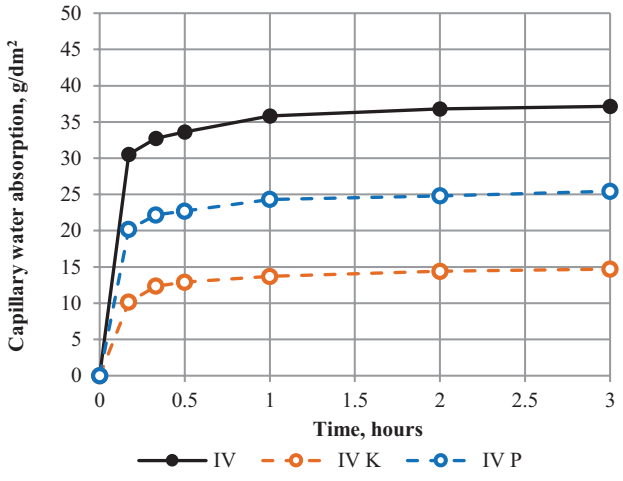

Fig. 12. Test results of capillary water absorption (first 3 hours).

Specimens prepared from the mixture using granules of ceramsite have shown lower values of the coefficient of capillary absorption than the specimens prepared from the mixture using EG granules as porous aggregate (comparing the data obtained accordingly from mixtures IV K and IV P). It can be explained by the structure of obtained material. For mixture IV K it was less porous and more dense (density of the mixture is 635 kg/m^3), but for mixture IV P the structure was more porous and less dense (density of the mixture is 376 kg/m^3).

The graph (see Fig. 13) presents the compared data of capillary kinetic of the experimentally prepared FC samples to the values of capillary absorption of similar density (400 kg/m^3 and 500 kg/m^3) commercially available (UAB "Aeroc") autoclaved aerated concrete (AAC) specimens (designations of the specimens accordingly are GB 400 and GB 500).

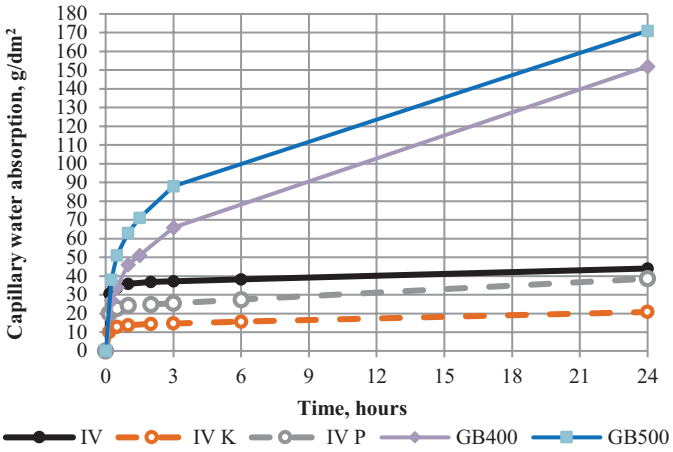

Fig. 13. Test results of capillary water absorption (full 24 hour test), comparing experimental FC specimens with commercially available AAC.

Test results (see Fig. 13) showed that the specimens of AAC have higher values of capillary absorption than the specimens of FC. Comparing the samples of GB 500 with the samples from reference mixture IV (without porous aggregate), it can be noticed that AAC shows about 70 % higher values of the coefficient of capillary water absorption than FC. This can be explained by the pore structure of these materials: the pore structure of FC is mostly closed while the pore structure of AAC – opened. The formation of the pore structure mainly depends on the technology of manufacturing (for AAC it is processing in autoclaves).

C. Shrinkage

For determination of drying shrinkage, the prismatic specimens were weighted and placed in the measuring instrument to obtain readings of the length changes of the specimens, comparing to the previous readings taken. Humidity meter – sensor was also used to obtain the values of relative humidity.

The results of shrinkage test are summarized in the graph (see Fig. 14) where the values of shrinkage (mm/m) are interpreted depending on the time (days) of the hardening process of the specimens. The test started after 7 days of hardening and was finished after 38 days of hardening.

Research results showed that the process of drying shrinkage is slower for the specimens of mixtures with porous aggregate added (EG granules for mixture IV P and granulated ceramsite for mixture IV K).

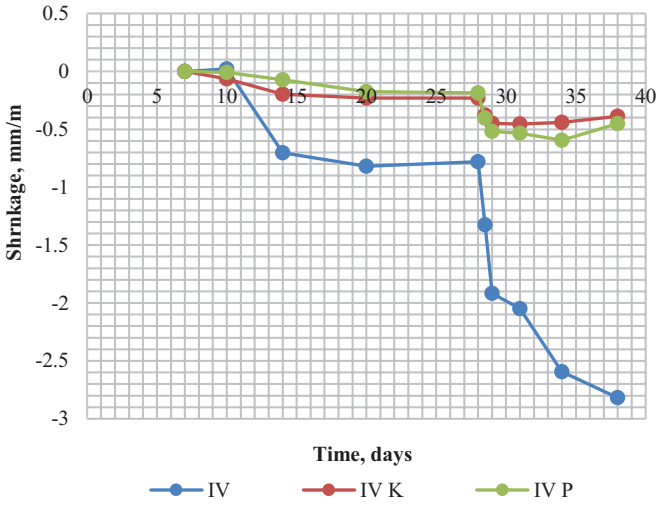

Fig. 14. Test results of drying shrinkage (mm/m) (full 38 days test).

For example, the value of drying shrinkage (after 28 days of hardening) of mixture IV is 0.780 mm/m, while that of mixture IV K and IV P is about 70 % and 76 % lower (0.231 mm/m and 0.187 mm/m accordingly). It can be explained by porous structure of the used aggregate – granulated expanded glass and ceramsite. Water entrained in the pores of light aggregate later in the process of hardening moves to the fine pores of the cement matrix. In this case the porous aggregate performs several functions at the same time. They not only fill the volume of FC matrix, but also supply additional water in the processes of drying and hardening; the specimens of composite FC demonstrated internal curing. That is why the samples with porous aggregate are not able to shrink and dry so fast as the samples without the porous aggregate.

To characterize drying shrinkage properties, a graph has been created (see Fig. 15), where the obtained data of the values of shrinkage (mm/m) and water loss (g) are summarized.

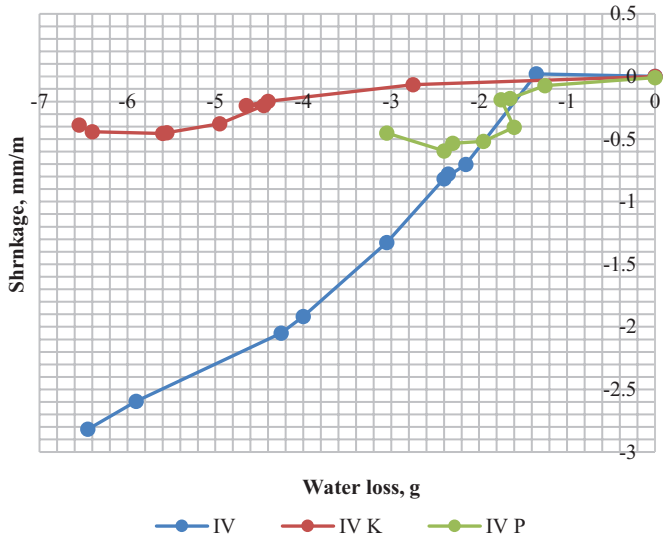

Fig. 15. Test results of drying shrinkage – water loss.

The process of drying shrinkage was faster for the specimens of mixture IV (without porous aggregate). Tested specimens of mixtures IV K (granulated ceramsite as an aggregate) and IV P (granules of EG as an aggregate) showed slower dynamics of the drying process, it resulted in lower values of the drying shrinkage.

For example, at the end of the test (38 days after hardening) the shrinkage value of mixture IV was 2.819 mm/m, but the values of the mixtures with light and porous aggregate were 0.387 mm/m (mixture IV K) and 0.452 mm/m (mixture IV P); the drying shrinkage values of the mixtures where porous aggregate was used were accordingly about 63 % and 52 % lower.

To visualize of the obtained data (to show the influence of water loss on the properties of drying shrinkage), a graph has been created (see Fig. 16).

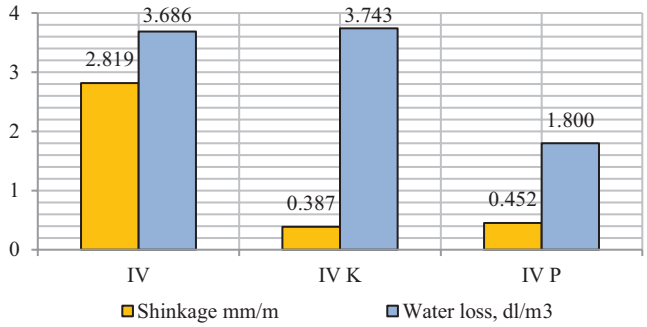

Fig. 16. The influence of water loss on the values of drying shrinkage (data obtained from the last readings taken – after 38 days of hardening).

It can be noted that the process of drying (or water loss) has the greatest influence on the reference mixture (without porous aggregate) IV. The value of water loss for the specimens of this mixture is 3.686 dl/m^{3}and the value of drying shrinkage – 2.819 mm/m, while the value of water loss of mixture IV K is similar (3.743 dl/m^3) but the shrinkage value is lower – 0.387 mm/m. The drying process of the specimens obtained from mixture IV P was not so high (value of water loss 1.800 dl/m^3) and it resulted in low value of drying shrinkage – 0.452 mm/m. Research results showed that the process of drying shrinkage of the specimens from the reference mixture IV has been proportional to the lost quantity of water, while for the mixture with granulated ceramsite water loss is greater (the process of drying) but the shrinkage value is low. Similar situation is observed for the mixture with granulated EG – small values of shrinkage and moderate water loss. It can be explained by the process of internal curing caused by the used porous aggregate. Lightweight aggregate fill the matrix of FC, making up its volume and supplying additional water for the process of curing. The used aggregate does not shrink and helps reduce the process of drying shrinkage in FC.

V. Conclusion

Research results have shown that using lightweight and porous aggregate in the preparation process of FC samples, it is possible to reduce the density of FC samples by 54 % (comparing to the samples of the reference mixture). With reduction of density and increase of porosity, these samples showed about 33 % lower values of compression strength (after 28 days of hardening) than the samples made from the reference mixture.

Efficiency of the used porous aggregate (granulated EG and ceramsite) resulted in better results of capillary water absorption test. The capillary transport in the specimens prepared from the mixtures where porous aggregate was used was not as intensive as in the specimens from the reference mixture. In this research, specimens with 34 % (from the mixture IV P with EG granules) and 86 % (from the mixture IV K with granulated ceramsite) lower values of the coefficient of capillary water absorption were obtained, comparing to the specimens prepared from the reference mixture. It is explained by the low water absorption ability of the used lightweight and porous aggregate. It will improve the durability of composite FC and will minimize the possibility of wetting in the process of exploitation.

It has been shown that the use of porous aggregate in the preparation of FC improves the properties of drying shrinkage of the specimens. Respectively, the processes of drying and shrinkage were slower for the samples from the mixtures with granulated EG and ceramsite. The values of drying shrinkage (after 38 days of hardening) were obtained about 52 % and 63 % lower (accordingly, from the mixtures with EG granules and ceramsite granules) than the values of samples from the reference mixture. Porous aggregate acts both as filler that forms the matrix of FC and small water reservoirs supplying additional water in the process of hardening, providing internal curing of FC samples. It would help to reduce the speed of the process of drying shrinkage and would also protect concrete from undesirable cracking.

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