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INCREASING THE CRACK RESISTANCE OF HIGH-STRENGTH SELF-COMPACTING CONCRETE

The object of research is high-strength self-compacting concrete, which does not require additional vibration during laying. One of the most problematic issues of high-strength self-compacting concretes is increased cracking, associated with large shrinkage deformations of such concretes and their fragile destruction.

A decrease in shrinkage deformations of concrete was established when part of the cement was replaced to mineral additives. This effect is explained by a decrease of the cement content and, accordingly, a decrease of the chemical component of the autogenous shrinkage of concrete, and an increase of the adsorptive binding of capillary moisture by mineral additives, with reduces the physical drying shrinkage of concrete. In this case, the type and dispersion of the used mineral additive can affect to the shrinkage deformations of concrete. A significant decrease in shrinkage deformations when using metakaolin is explained by an increase the amount of ettringite as a result of the reaction of active metakaolin Al_2O_3 *with two-water gypsum of cement. It was found that the replacement of cement to 10 % of mineral additives leads to a decrease in the value of the critical stress intensity factor (SIF), which is compensated by a decrease of the fragility of concrete fracture (an increase of the area of microplastic deformations). At the same time, the type of mineral additive used does not affect to the value of the critical stress intensity factor, but significantly affects to the fragility of fracture of concrete samples. The introduction of 10 % mineral additives (to replace cement) had a positive effect on the retention of flow of self-compacting concrete mixes; the best results according to this criterion were observed when using silica fume, fly ash and limestone. All mineral modifiers, except for silica fume, led to a decrease of the compressive strength of high-strength concretes on all terms of hardening. In the case of the tensile strength of concrete at bending and splitting, with the introduction of silica fume, metakaolin and fly ash, a positive effect was observed compared to the base composition without additives.*

Comprehensive accounting of the results obtained will allow a reasonable approach to the design of high-strength self-compacting concretes with increased crack resistance.

Keywords: *high-strength concrete, self-compacting concrete, crack resistance of concrete, flexural modulus, stress intensity factor.*

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1. Introduction

The use of high-strength self-compacting concretes, which do not require additional vibration, makes it possible to reduce the cross-section of concrete structures, and therefore their cost, while ensuring the same bearing capacity. At the same time, such concrete structures need to ensure the crack resistance of concrete, since crack formation can increase the permeability of the concrete of the structure to aggressive media, reducing their durability. The problem of cracking is especially relevant for self-compacting concretes, having greater shrinkage deformations than conventional concrete, and high-strength concretes characterized by brittle fracture. The solution to the problem of crack resistance of such concretes lies in the plane of the formulation – at the level of aggregates, binders, mineral and chemical admixtures.

Thus, taking into account the spread of the use of high-strength self-compacting concretes, characterized by increased shrinkage deformations and brittle fractures, it is relevant to study the possibilities of increasing their crack resistance at the recipe level. The problem of crack resistance of high-strength self-compacting concrete is especially relevant from the point of view of ensuring the durability of concrete structures with a reduced cross-section. Comprehensive accounting of the results of such studies will make it possible to reasonably approach the design of high-strength self-compacting concretes with increased crack resistance.

2. The object of research and its technological audit

The object of research is high-strength self-compacting concrete, which does not require additional vibration during laying. The following criteria can be used to control rheology of self-compacting concrete mix: flow diameter (>620 mm, class F6) and flow time up to ∅500 mm (3–5 s). Traditionally, concretes of strength classes C60 and more are considered high strength. The production of high-strength concretes involves the use of an increased amount of binders and a low water-cement ratio. An increased consumption of binders and dispersed fillers is required to ensure the ability of concrete mix to self-compacting. As a result, one of the most problematic issues of high-strength self-compacting concretes is increased cracking, associated with large shrinkage deformations of such concretes and their brittle destruction.

3. The aim and objectives of research

The aim of research is to increase the crack resistance of high-strength self-compacting concretes due to modification with mineral additives.

To achieve the aim, the following objectives are set:

1. To study the effect of silica fume, metakaolin, fly ash and limestone on the rheological properties of self-compacting concrete.
2. To investigate the efficiency of using silica fume, metakaolin, fly ash and limestone according to the strength criterion of high-strength concrete.
3. To assess the effect of mineral modifiers on the crack resistance of high-strength self-compacting concretes according to a set of criteria (shrinkage deformations, flexural modulus, critical stress intensity factor, fracture fragility).

4. Research of existing solutions of the problem

Self-compacting concrete (SCC), pioneered in Japan, does not require additional vibration for compaction, reduces confinement costs and improves working conditions [1]. The disadvantages of SCC include greater shrinkage compared to conventional concrete, which leads to an increase in cracking [2, 3]. The following main types of SCC shrinkage deformations are distinguished: autogenous shrinkage as a result of chemical reactions between cement and water, shrinkage as a result of evaporation (drying) of free water from the pores of hardened concrete, and plastic shrinkage of fresh concrete [4, 5]. While the autogenous shrinkage of the SCC can be at the level of that of conventional concrete, the drying shrinkage SCC is more significant. A decrease in the water-cement ratio and a higher cement content leads to an increase in the autogenous shrinkage of high-strength concretes. International studies show that SCC shrinkage is 10–50 % higher than that of conventional concrete [6]. In this case, concrete cracking begins when tensile stresses reach the ultimate tensile strength [7]. Usually, shrinkage cracks in SCC are observed in the early stages of hydration [4, 8]. Thus, studies of restrained shrinkage of concrete indicate that SCC cracking began in 8–13 days, while ordinary concrete did not have shrinkage cracks up to 28 days [9].

To reduce shrinkage deformations of concrete, it is recommended to provide proper curing [1]. Also, for this purpose, mineral and chemical expansion and shrinkage reducing agent (SRA) are used [10, 11]. SRAs prevent drying shrinkage cracking by reducing the evaporation of water from the capillary pores of the concrete, but can negatively affect the rheological properties of concrete mixes. An increase in the crack resistance of concrete is also achieved with the addition of reinforcing fibers, which also lead to deterioration of the rheology of concrete mixes SCC [12, 13].

The higher content of fine fractions of fillers and cement leads to an increase the content of cementitious paste in SCC than in conventional concrete, which increases the autogenous shrinkage and drying shrinkage of concrete [4, 14]. However, the value of SCC shrinkage is also influenced by other factors, in particular those related to capillary pressure [15]. Thus, SCC shrinkage can be reduced by using fillers such as silica fume [16], fly ash and limestone [17]. Known positive effect on reducing concrete deformations caused by physical and chemical factors, metakaolin additives [18, 19].

It should be noted that the risk of cracking depends not only on shrinkage, this parameter is also influenced by such properties of concrete as flexural modulus, creep, tensile strength, etc. [20]. All these properties should be taken into account when assessing the crack-resistance of SCC [21]. However, there are not enough results of comprehensive studies of such properties of SCC in the literature. An attempt at a comprehensive assessment of the crack-resistance of SCC with limestone and silica fume by taking into account the properties that affect to the risk of fracturing (shrinkage, flexural modulus, creep, fracture parameters) are given in [2]. The presented results of modeling of crack-resistance coincide with the results of testing of cracking by SCC method with restraining ring (RRTM) [22]. It is expedient to carry out such complex studies of SCC with fly ash and metakaolin, which are characterized by the presence of active Al_2O_3 in the composition and can have a significant effect on the crack resistance of concrete [18, 19].

So, according to the results of the literature review, it is possible to note the possibility of increasing the crack resistance of high-strength self-compacting concretes (without deteriorating rheology of concrete mixes) by modifying them with mineral additives (silica fume, limestone, fly ash and metakaolin). This requires a comprehensive study of shrinkage, flexural modulus and parameters characterizing the cracking of modified concrete.

5. Methods of research

Portland cement CEM I 42.5 R (Public Joint Stock Company «Podilskyi Cement», CRH, Ukraine) was used in the research. Mineral additives: metakaolin METAVER I (NEWCHEM AG, Austria), silica fume Microsilica 940 (Elkem, Norway), limestone (State Enterprise Zakupnianskyi Quarry, Ukraine), fly ash (Ladyzhyn heat power plant, Ladyzhyn, Ukraine). Aggregates: river quartz sand, granite crushed stone of 5–10 and 10–20 mm fractions. Superplasticizers admixtures produced by MC-Bauchemie, Germany.

Physical and mechanical studies were carried out in accordance with the current regulatory documents. Concrete mixes were tested with DSTU EN 206:2018, DSTU B V.2.7-176:2008, DSTU B V.2.7-96-2000 and DSTU B V.2.7-114-2002. The strength of concrete was determined according to DSTU EN 206:2018, DSTU B V.2.7-176:2008, DSTU B V.2.7-214:2009, DSTU B V.2.7-224:2009. The flexural modulus of concrete was determined in accordance with DSTU B V. 2.7-217:2009. The parameters of crack resistance (stress intensity factor) of concretes under static load were determined on prismatic specimens with an initiated crack in accordance with DSTU B V.2.7-227:2009.

6. Research results

6.1. Effect of mineral additives on the rheological properties of self-compacting concrete mixes. The study of the influence of mineral additives on the rheological properties of self-compacting concrete mixes was carried out according to the following criteria: flow diameter, flow time up to ∅500 mm and retention of flow over time.

Composition of concrete mixes were characterized by a constant water-cement ratio (W/C=0.3). Composition No. 1 (basic) was characterized by a content of 500 kg/m^3 CEM I 42.5. The following mineral additives were used: silica fume, limestone, metakaolin in an amount of 10 % to replace cement.

The rheological properties of the concrete mixes were monitored at three time intervals: 15 min, 60 min and 120 min after mixing with water. The flow diameter (>620 mm, grade F6) and the flow time up to ∅500 mm (3–5 s) and their retention over time were used as requirements for the rheological properties of self-compacting concrete mixes.

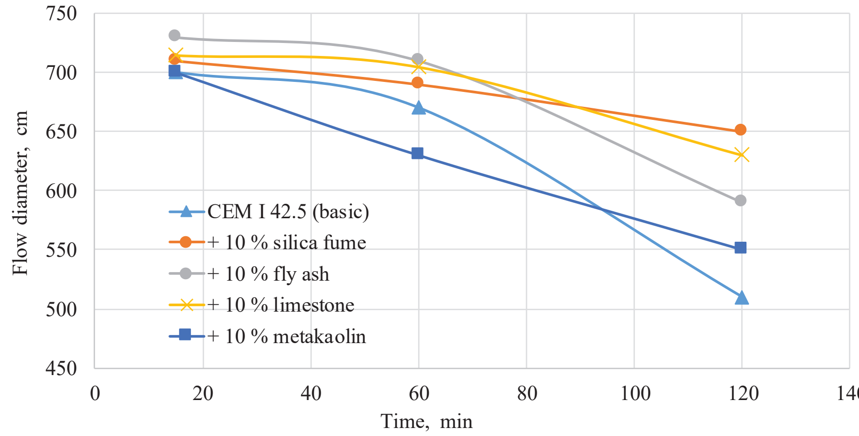

Fig. 1. Flow diameter of concrete mix in time

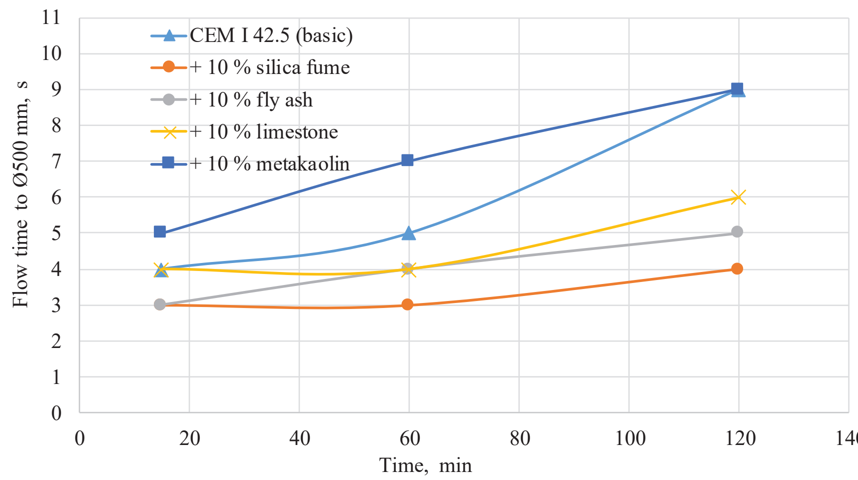

Fig. 2. Flow time of concrete mixes to a diameter of 500 mm

The basic composition of the concrete mix, with a consumption of Superplasticizers (SP) of 1 % of the cement mass, was characterized by the flow class F6 only for 60 minutes, and after 120 minutes the flow class decreased to F4 (Fig. 1). A concrete mix with 10 % fly ash at 1 % SP, was also characterized by flow class F6 for 60 min, which was F5 after 120 min (Fig. 1). At the same time, the concrete mix with 10 % silica fume, which required an increased a consumption of SP (1.35 % of the binder mass), was characterized by flow class F6 for 120 min.

Similar results were observed in the concrete mix with a content of 10 % limestone and 1 % SP, and was also characterized by flow class F6 for 120 minutes. The use of 10 % metakaolin to replace cement leads to a significant increase in the water demand of the concrete mix or an increase in the SP consumption to 1.4 % of the binder mass. The concrete mix corresponded to the flow class F6 within 60 minutes, and after 120 minutes – to the flow class F4 (Fig. 1).

In general, as can be seen from Fig. 1, in all concrete mixes, a regular loss of flow is observed, especially noticeable after 120 minutes, which occurs faster in the case of the basic composition of the concrete mix without mineral additives with the highest cement consumption.

The flow time of the concrete mixes under study up to ∅500 mm (Fig. 2) reproduces the basic laws noted above. The indicator of flow time up to ∅500 mm – 3–4 s for 120 min was characterized the concrete mix with silica fume. Concrete mix with fly ash was characterized by flow time up to ∅500 – 4–5 s for 120 min. Concrete mix with limestone, had flow time up to ∅500 4 s for 60 min and 6 s after 120 min.

With the introduction of metakaolin, was a significant slowdown of flow time of the concrete mix was observed up to 5–9 s at all control time intervals. The basic composition of concrete without mineral additives was characterized by a significant loss of the flow time (9 s) after 120 min.

Thus, according to the flow criterion, all investigated concrete compositions can be used for the production of precast concrete structures. At the same time, according to the criterion of retention of flow for 120 minutes for the production of cast in situ concrete structures, it is possible to recommend only concrete with silica fume, fly ash and limestone.

6.2. Study of the influence of mineral additives on the strength of high-strength concrete. The study of the efficiency of introducing 10 % (by weight of the binder) mineral additives according to the criterion of the compressive strength of concrete, splitting tensile strength and flexural strength are shown in Fig. 3–5, respectively.

As seen from Fig. 3, the greatest strength on the 3rd day of hardening (60 MPa) is characteristic of the basic composition of concrete without mineral additives. The lowest strength for 3 days (46.5 MPa) has the composition of concrete with fly ash. The best result on the 28th day (84.7 MPa) is observed with the addition of silica fume. With the introduction of 10 % limestone on the 28th day, the lowest strength (66.9 MPa) was observed. On day 90, the strength of all investigated concrete compositions corresponded to the classes C60/75–C70/85. The introduction of silica fume made it possible to obtain the concrete strength class C70/85 (93.5 MPa).

The study of the splitting tensile strength of high-strength concretes shows (Fig. 4), the introduction of 10 %

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limestone reduces this indicator to 4.7 MPa in comparison with the basic composition (5.5 MPa). When using 10 % fly ash and metakaolin, there is a slight increase in splitting tensile strength up to 5.8 MPa. The introduction of 10 % silica fume into the concrete composition increases the splitting tensile strength up to 6.4 MPa.

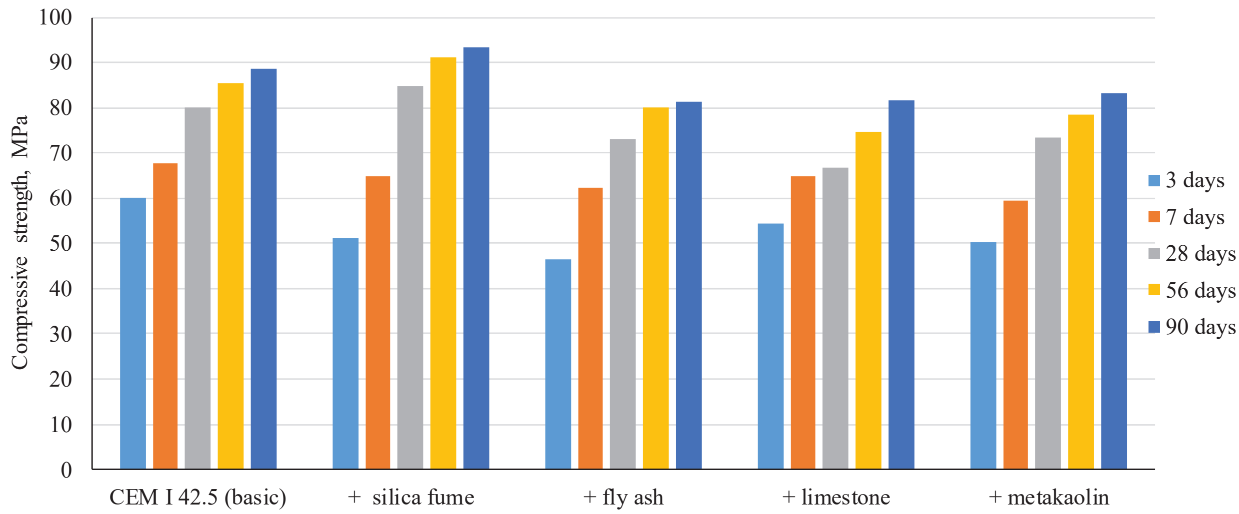

Fig. 3. Compressive strength of high-strength concrete

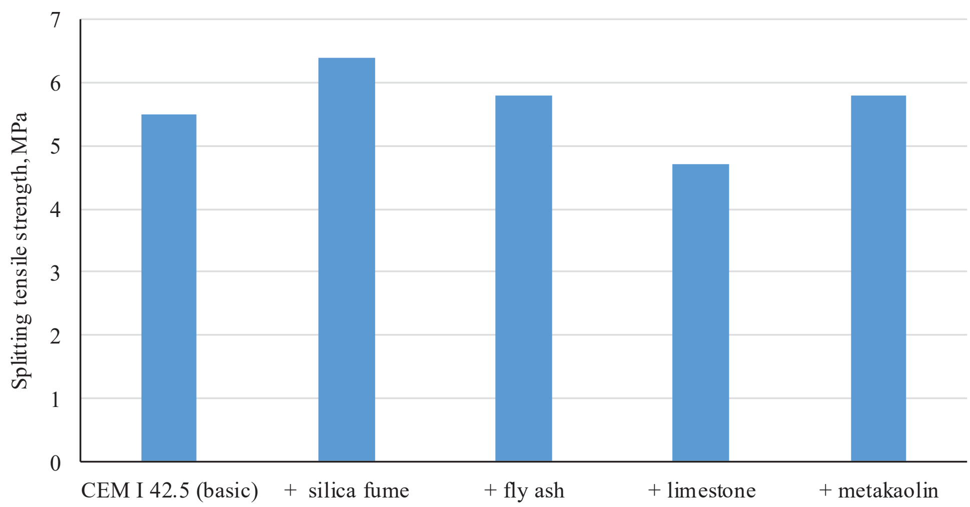

Fig. 4. Splitting tensile strength of high-strength concrete

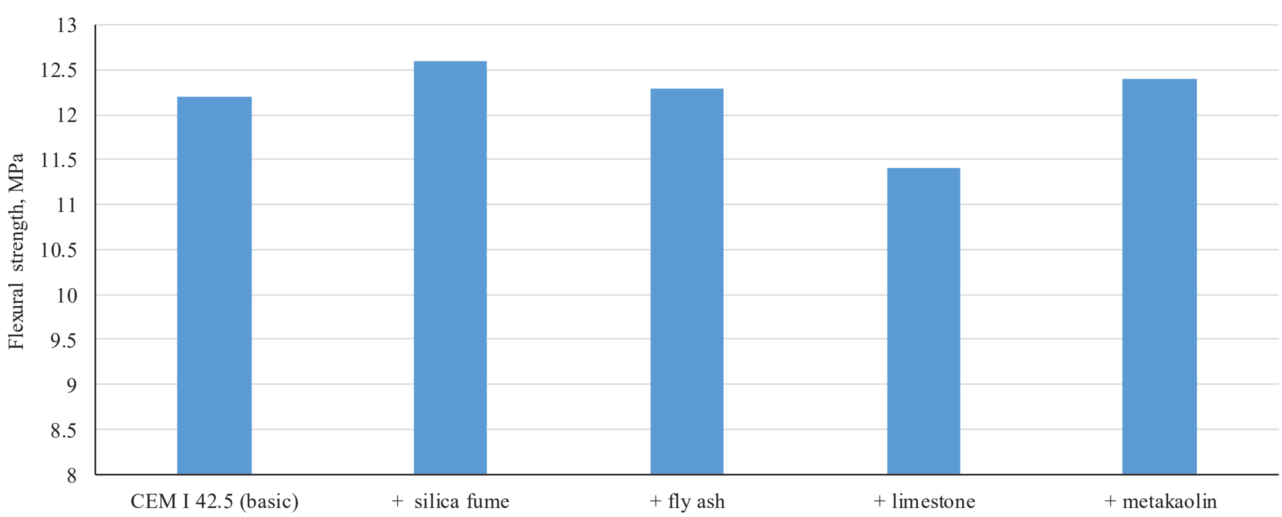

Fig. 5. Flexural strength of high-strength concrete

The results of studies of the flexural strength of high-strength concrete (Fig. 5) reproduce the basic laws given above. Concrete compositions with 10 % fly ash and metakaolin slightly exceeded the flexural strength of the base composition (12.3–12.4 MPa). The introduction of 10 % silica fume made it possible to increase the flexural strength of concrete up to 12.6 MPa. The introduction of 10 % limestone reduced the flexural strength of concrete to 11.4 MPa.

Thus, according to the strength criteria, all the formulations under study can be classified as high-strength concretes of C60/75–C70/85 classes. The highest strength indicators were characteristic of the composition of concrete with 10 % silica fume.

The base composition of concrete and compositions with 10 % fly ash and metakaolin had slightly lower strength. The lowest strength indicators were the composition of concrete with 10 % limestone.

6.3. Study of the effect of mineral additives on the deformative properties of high-strength concretes. The main reasons for the formation of cracks in concrete are shrinkage deformations. There are two main components of shrinkage deformations of concrete: deformations resulting from the drying shrinkage of concrete, which is a physical process, and autogenous shrinkage deformations due to chemical reactions between cement and water. The cement content in concrete predominantly affects the value of the chemical (autogenous) component of shrinkage. Dispersed mineral component affects of the physical (adsorption) binding of capillary moisture in the pores of concrete and, accordingly, the value of the drying shrinkage.

Fig. 6 shows the results of a study of shrinkage deformations of high-strength concretes with mineral additives on samples – prisms (500x100x100 mm) for 120 days in air-dry conditions. The introduction into the composition 10 % of fly ash, silica fume and limestone made it possible to reduce shrinkage deformations by 120 days to 0.34–0.36 mm/m. The introduction of 10 % metakaolin reduced shrinkage to 0.29 mm/m with shrinkage of the base composition without additives, reached 0.38 mm/m. At the same time, on the 7th day of hardening, the basic composition of SCC was characterized by a lower shrinkage (0.06 mm/m) than compositions with mineral additives (0.11–0.14 mm/m).

Restrained shrinkage deformations of concrete can lead to stresses exceeding the tensile strength of concrete and cause cracking. In this case, the stress of concrete arising from its deformation is directly proportional to its flexural modulus.

According to the results of studies of the flexural modulus of concrete (Fig. 7) at the age of 56 days, the composition of concrete with 10 % metakaolin was characterized by a low flexural modulus of 36.6 GPa.

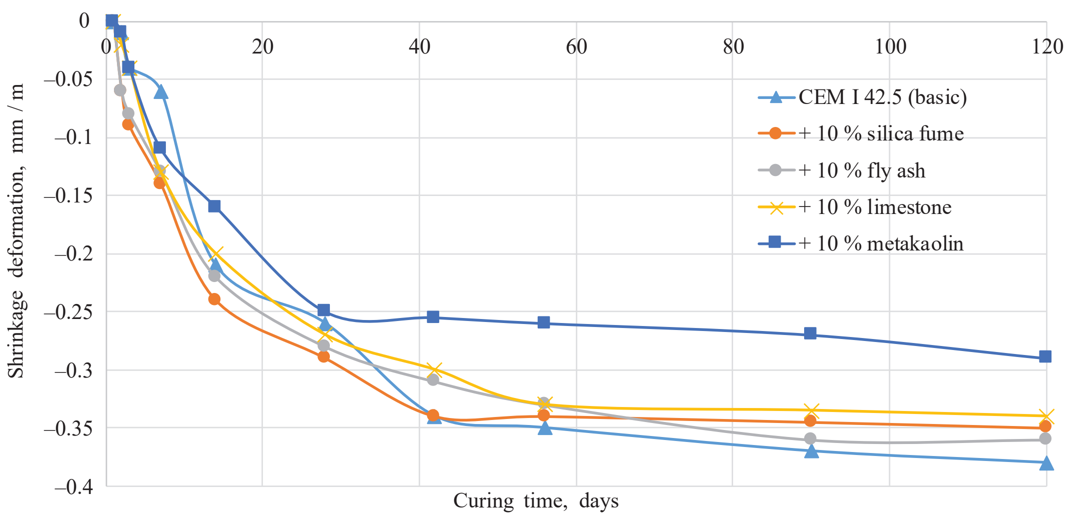

Fig. 6. Shrinkage deformations of high-strength concrete

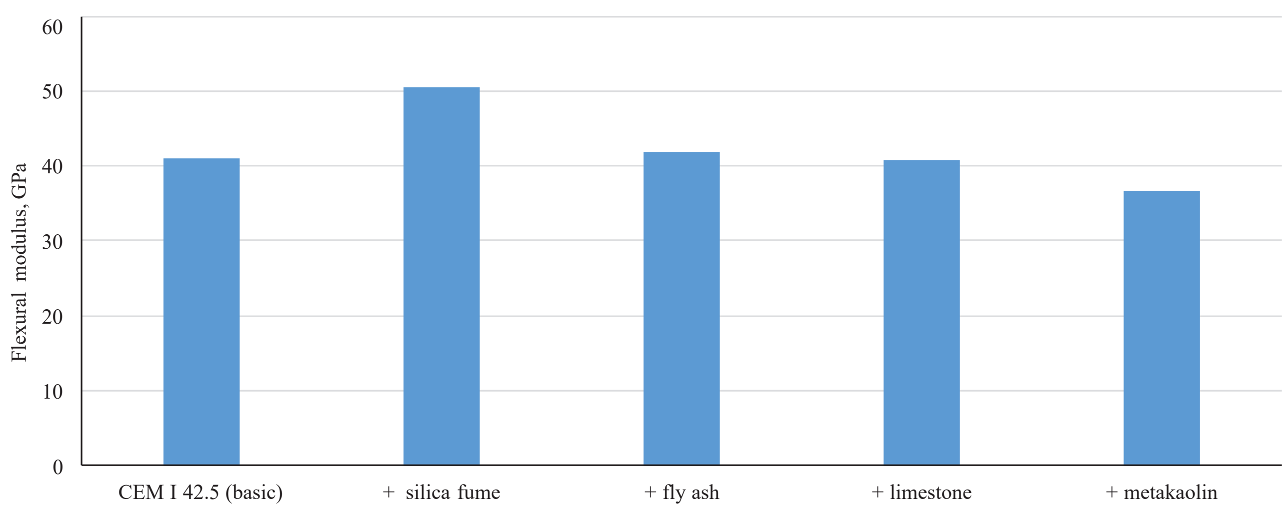

Fig. 7. Flexural modulus of the investigated concretes

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The flexural modulus of 41–42 GPa were characterized by concretes of basic composition and compositions of concrete with 10 % fly ash and limestone. A high flexural modulus of 50.4 GPa was characteristic of the composition of concrete with 10 % silica fume.

The assessment of the crack resistance of high-strength concretes was carried out with an indicator of the critical stress intensity factor (SIF) Kic. The value of the critical SIF corresponding to the onset of microcracking was determined from the bending deformation diagrams of prismatic specimens of concrete with an initiated crack, as the end of the linear section (0–1) of elastic deformation of the material (Fig. 8).

The size of the area of microplastic deformations (1–2) was considered as an indicator of the fragility of concrete fracture, which corresponds to the difference between the deformations of the beginning of micro-cracking (1) and the beginning of the formation of a main crack (2).

As seen from Fig. 9, according to the criterion of critical stress intensity factor, concrete of basic composition can be considered the most crack-resistant, characterized by Kic – 0.85 MPa $m^{1/2}$. This indicator for concretes with 10 % mineral additives is Kic – 0.74–0.76 MPa $m^{1/2}$ and increases in a number of concrete with metakaolin, limestone, fly ash and silica fume.

As seen in Fig. 10, the most fragile fracture had samples of concrete of basic composition (area of microplastic deformation ~7 μm). The least fragile fracture – samples of concrete with fly ash and metakaolin (areas of microplastic deformation ~13.5 and 12.5 microns, respectively). Samples of concrete with silica fume and limestone (areas of microplastic deformation ~10 and 10.5 μm, respectively) had average indicators of fragility of fracture.

Each of the indicators considered above allows one to separately judge the deformation properties of high-strength concretes, however, for a more accurate assessment of crack resistance, it is advisable to consider them in a comprehensive manner. At the same time, the assessment of the crack resistance of concrete by a set of criteria can be difficult. Thus, concrete of the basic composition is simultaneously characterized by the highest shrinkage deformations of 120 days and the highest values of the critical stress intensity factor. The composition of concrete with metakaolin, although it has low shrinkage deformations and flexural modulus, is characterized by a low value of the critical stress intensity factor. So, it is expedient to carry out a comprehensive assessment of concrete crack resistance according to the considered criteria by modeling crack formation, for example, by the finite element method [23].

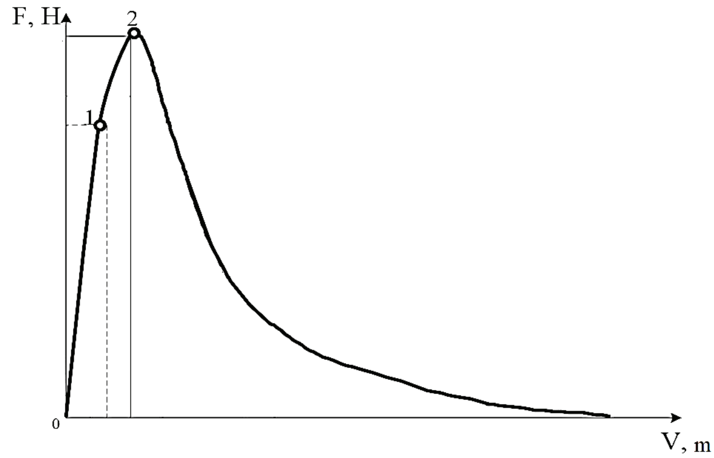

Fig. 8. Bending deformation diagram of a concrete prism with an initiated crack

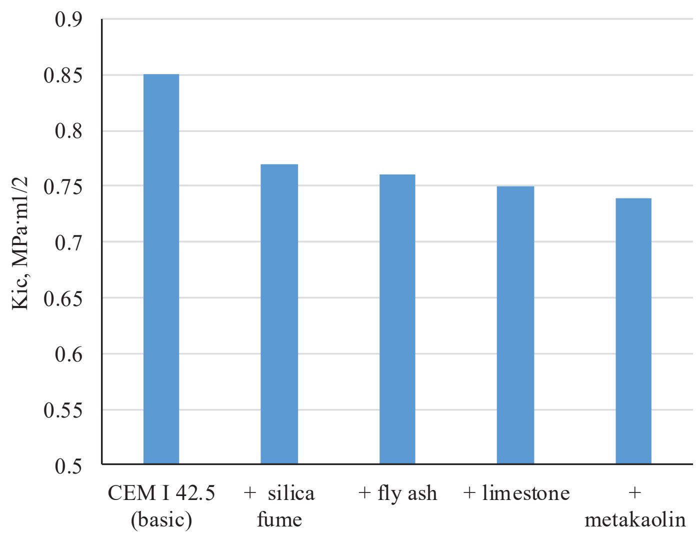

Fig. 9. Critical stress intensity factors

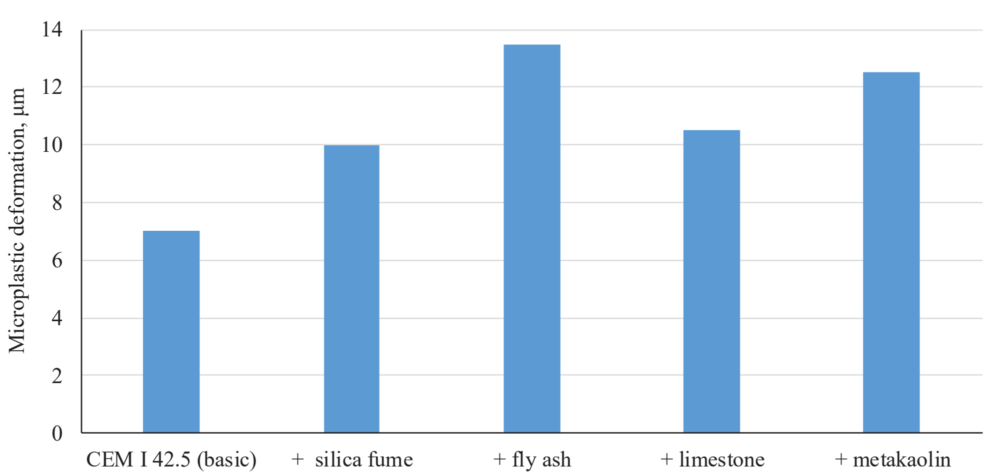

Fig. 10. Size of the area of microplastic deformation

7. SWOT analysis of research results

Strengths. As can be seen from the research results, the replacement of cement by 10 % of mineral additives had a positive effect on the retention of flow of self-compacting concrete mixes, which is explained by a decrease in the cement content. The best indicators of retention of flow were obtained using silica fume, fly ash and limestone. At the same time, an increase of the compressive strength in comparison with the base composition without additives was observed only when using 10 % silica fume. All other mineral modifiers led to a decrease of the compressive strength of concrete at all times of hardening. In the case of concrete flexural strength and splitting tensile strength, introduction (to replacing cement), 10 % of silica fume, metakaolin and fly ash had a positive effect compared to the base composition without additives. This effect is explained by an increase in the content of low-calcium hydrosilicates in the products of cement hydration with pozzolanic additives [18].

According to the results of the study of shrinkage of high-strength concretes, a positive effect of replacing part of the cement with mineral additives can be noted. This is due to the effect of a decrease in the cement content and, accordingly, a decrease in the chemical component of autogenous shrinkage of concrete. The effect of the dispersed mineral component also takes place, enhances the adsorptive binding of capillary moisture and, thus, reduces the physical drying shrinkage of concrete. A significant decrease in shrinkage deformations when using metakaolin can't be explained only by physical factors, as in the case of other mineral additives. This effect is associated with an increase the amount of ettringite as a result of the reaction of active Al_2O_3 metakaolin with two-water gypsum of cement [18].

Weaknesses. Replacing cement with 10 % mineral additives leads to a decrease in the value of the critical stress intensity factor, which is compensated by a decrease in the fragility of fracture of concrete (an increase in the area of microplastic deformations). At the same time, the type of mineral additive does not affect the value of the critical stress intensity factor, but significantly affects the fragility of fracture of concrete samples. Such effects can be explained by quantitative and qualitative changes in the cement matrix that occur when mineral additives are introduced to replace cement and require additional physicochemical studies.

Each of the considered indicators allows one to separately judge the deformative properties of high-strength concretes, however, for a more accurate assessment of crack resistance, it is advisable to consider them comprehensively. However, the assessment of the crack resistance of concrete by a set of criteria can be difficult. For example, basic concrete is simultaneously characterized by the largest shrinkage deformations and the largest values of the critical stress intensity factor. The composition of concrete with metakaolin has the lowest shrinkage deformations and flexural modulus, however, it is characterized by a low critical stress intensity factor. In this work, the values of the flexural modulus and the parameters of concrete destruction were determined at the age of 56 days, while, according to the literature data, SCC cracking can occur at an earlier time of hardening. When assessing the crack resistance of concrete, it is advisable to take into account creep deformations, which can significantly affect the stress relaxation in concrete, which hardens.

Opportunities. The development of the above studies is assumed in the modeling of cracking in order to comprehensively assess the SCC crack resistance according to the criteria of shrinkage, creep, flexural modulus, critical stress intensity factor at different hardening periods. An explanation of the obtained results is expected to be obtained based on the results of physical and chemical research.

Threats. Increased cracking, inherent in high-strength self-compacting concretes, can significantly to raise the permeability of concrete structures to aggressive agents, reducing their corrosion resistance and durability. Ensuring the regulated crack resistance (durability) of such concretes requires additional measures at the formulation level (use SRA and fiber) and curing (use curing products). So, solving the problem of cracking of high-strength self-compacting concretes of requires additional costs, which can reduce the economic efficiency of their use.

8. Conclusions

1. The effect of 10 % mineral additives (to replacing cement) on the rheological properties of self-compacting concrete mixes according to the criteria of flow diameter (>620 mm, class F6) and flow time to a diameter of 500 mm (3–5 s) was investigated. It was found that according to these criteria, all investigated concrete compositions can be used for the production of precast concrete structures. However, according to the criterion of retention of flow for 120 minutes, only concrete with silica fume, fly ash and limestone can be recommended for the production of cast in situ concrete structures.

2. The efficiency of introduction of 10 % silica fume, metakaolin, fly ash and limestone was investigated according to the criteria of compressive and tensile strength of concrete. It was found that in terms of compressive strength all the compositions under study can be attributed to high-strength concretes of C60/75–C70/85 classes. The highest compressive strength indicators were characterized by the composition with silica fume (93.5 MPa), the basic composition of concrete (88.5 MPa) and the composition of concrete with metakaolin (83.1 MPa). The highest indicators of flexural strength (12.3–12.6 MPa) and splitting tensile strength (5.8–6.4 MPa) had the compositions of concrete with silica fume, metakaolin and fly ash.

3. The influence of mineral modifiers on the crack resistance of high-strength concretes was investigated according to the criteria of shrinkage, flexural modulus and critical stress intensity factor. It was found that, in comparison with the shrinkage of the base composition without additives (0.38 mm/m), the compositions of concrete with 10 % fly ash, silica fume and limestone on 120 days are characterized by shrinkage deformations of 0.34–0.36 mm/m. Introduction 10 % metakaolin reduces shrinkage to 0.29 mm/m. At the same time, on the 7th day of hardening, the basic composition of SCC is characterized by less shrinkage (0.06 mm/m) than compositions with mineral additives (0.11–0.14 mm/m). It was found that the lowest index of the flexural modulus (36.6 GPa) is characterized by concrete with metakaolin, and the highest (50.4 GPa) – concrete with silica fume. Flexural modulus 41–42 GPa have concretes of basic composition and composition with fly ash and limestone. According to

the criterion of critical stress intensity factor, the most crack-resistant can be considered basic composition of concrete, characterized by a critical stress intensity factor of 0.85 MPa $m^{1/2}$. This indicator for concretes with 10 % of mineral additives is 0.74–0.76 MPa $m^{1/2}$ at the same time, the basic composition of concrete had the most fragile destruction (area of microplastic deformation ~7 μm). The least fragile destruction had the compositions of concrete with fly ash and metakaolin (areas of microplastic deformation ~13.5 μm and 12.5 μm, respectively). Compositions of concrete with limestone and silica fume (areas of microplastic deformation ~10.5 and 10 μm, respectively) had average indicators of fragility of fracture.

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