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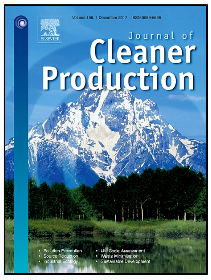

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Abstract

Nowadays green buildings are a necessary component of securing sustainability, whereas concrete composites with the addition of siliceous fly ash (FA) can certainly be included in the sustainable and green concrete. Effective promotion of green concrete incorporating FA is required in order to minimize the environment threat due to FA waste disposal and reduce cement consumption.

In this paper, effects of FA addition on the compressive strength f_{cm} and fracture toughness of plain concrete are presented. Fracture toughness tests were carried out according to Mode I (tension at bending) following the RILEM Draft Recommendations. The critical values of stress intensity factors, K_{Ic}^{S} have been determined.

To assess mechanics parameters compressive strength tests and fracture toughness tests were conducted and the results were evaluated comparing with reference concrete. In modified concretes, cement was replaced by FA by its weight. Three test groups were constituted with the replacement percentages as: 0% (FA-00), 20% (FA-20) and 30% (FA-30). During the tests, the effect of age of concretes modified with the additive of FA on analysed parameters was determined. The experiments were carried out after: 3, 7, 28, 90, 180 and 365 days of curing.

Based on the obtained results it can be concluded that, it is possible to make green concrete containing FA with high compressive strength and fracture toughness. The properties of composites with the additive of FA depend on the age of the concrete during tests. 20%

additive of FA guarantees high f_{cm} and K_{Ic}^{S} in mature concretes. Moreover results of the K_{Ic}^{S} and the f_{cm} are convergent qualitatively.

Keywords:, green concrete composite, fly ash, compressive strength, fracture toughness, critical stress intensity factor, curing time.

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1. Introduction

Nowadays, principles of sustained development and ecology are an important issue in design of concrete compositions. Furthermore, the conservation of resources and environment for a sustainable future has been today's one of the biggest challenges (Gursel et. al., 2016). Changes resulting from more and more frequent use of hybrid cements in the concrete technology based on mineral additives, which are by-products of other industrial or agricultural processes, have a beneficial effect on not only the reduction of CO_2 emission but also constitute the basis of the so-called sustainable – green concrete concept (Aitcin, 2000; Meyer, 2009; Yang et. al., 2016).

Structures made of green concrete are environmentally sustainable and are constructed in such a way that the total impact on the environment during their full life cycle, including service life, is reduced to a minimum. In this context, responsible green construction should be energy efficient and made of environmentally friendly materials. Concrete used in such structures must meet the requirements for strength and durability and its components should be obtained, produced and used in an environmentally friendly manner (Aitcin, 2000; Jayapalan and Lee, 2013). Furthermore, green buildings are a necessary component of securing sustainability. According to Thatcher and Milner (2016) health, wellbeing, and effectiveness in green buildings is an important motivator for their occupants. Interesting proposal and suggestions for designing more sustainable and greener concrete were proposed by Long et. al. (2015).

It should be noted that in the last several dozen years, with the development of a new generation of composites, i.e. green concrete composites, significantly increased the production of concrete mixtures containing different types of supplementary cementitious materials (SCMs) (Lothenbach et. al., 2011). According to Aprianti (2017), Paris et. al. (2016), Nagaratnam et. al. (2016) and Mo et.al. (2016) these materials can be divided generally into:

- industrial wastes, such as: fly ash (FA); including calcareous and siliceous, silica fume (SF), ground granulated blast furnace slag (GGBFS),
- agriculture-farming wastes, such as: bamboo, wheat, barley, corn, olive, banana, sisal, date palm, elephant grass,
- aqaculture-farming wastes, such as: oyster, periwinkle, mussel.

Cement substitution by other materials is important for sustainable construction because production of Ordinary Portland Cement (OPC) not only uses a considerable amount of energy, but also emits a substantial amount of CO_2 and other greenhouse gases (Mehta, 2002). The production of one ton of OPC requires 4 GJ of energy and emits approximately 1.35 billion tons of CO_2 into the atmosphere annually (Mehta, 2001). It is estimated that the CO_2 released during cement clinkering is around 0.7 to 0.9 tons per ton of Portland cement, meaning that the cement industry generates around 7% of total CO_2 emissions worldwide (Keun-Hyeok, 2013).

For that reason, utilization of SCMs has been found as a suitable alternative to reduce CO_2 emissions from cement production (Kotwica et. al., 2017). From the other hand, FA is the most well-known of these materials and has been used for decades in cement applications. Among these applications, the most significant is the replacement of clinker in cement blends, which reduces the consumption of resources and energy and at the same time, avoids the environmental burden associated with clinker production (Vargas and Halog, 2015; Acharya and Patro, 2016). Additionally, according to environmental protection agency (EPA, 2008) the use of FA in concrete reduces the greenhouse emissions equivalent to emissions from 2.5 milion cars on road every year. Assuming that the average car travels for about 10.000 km a year, this corresponds to the equivalent of roughly 4.2 million tons of FA. Hence, significant reduction in greenhouse emissions can be achieved by increasing the utilization of FA in concrete (Hemalatha and Ramaswamy, 2017).

Concrete composites with the addition of siliceous FA can certainly be included in the sustainable and green concrete category also for the following reasons. Utilization of industrial wastes such as FA is important from the ecological and economical points of view. In addition, procedures of this type, very important for the protection of the environment, are a part of a sustainable development strategy (Mehta, 2002). This situation occurs, e.g. in Poland. Since thermal and electrical energy in Poland in more than 90% is produced in coal combustion processes, approximately 20 million tons of siliceous FA is produced each year (Kurdowski, 2014). Such large quantities of waste in the absence of its management require the construction, maintenance and protection of facilities responsible for those wastes, which is a major environmental and social problem. In order to reduce large quantities of FA, the by-products of coal combustion in 20th century began to be used as a nutritious additive for cement and concrete. Currently, the cement industry is one of the major areas of the economy, which on a large scale is able to utilize emerging, in the hard coal combustion processes, combustion by-products which are FA. Treatments of this type are beneficial for ecological reasons due to reducing the deposit areas of troublesome industrial wastes as well as the economic reasons because of the possibility to replace part of the cement binder in the concrete with FA treated as pozzolanically active microfillers.

Issues of substitution of cement binders with the siliceous FA, in addition to the scientific aspect, are also important in terms of applicability, from an economic point of view. Although for many years there has been a discussion on diversification of energy production, perspectives and strategies of the governments in many countries for the coming years, and even decades, it is predict that coal will remain a major source of energy. On the basis of Hemalatha and Ramaswamy (2017) coal usage is expected to increase 3.4% over the next 2 decades despite the retirement of many coal plants.

As siliceous FA is a by-product obtained in the process of hard coal combustion, there are hundreds millions tons of industrial waste produced annually across the World. Up to date – 750 million tones of the FA is generated each year in the World (Blissett and Rowson, 2012) and in the future one should expect to increase this quantity to 2100 million tones in 2031-32 (Hemalatha and Ramaswamy, 2017).

Nowadays, FA has been widely used in many research purposes. The main areas of development of FA are: construction, mining and terrain management. The analyses of use of FA in the construction industry reveal that more than 50% of this material is used in the cement industry as a cement replacement material. Therefore the FA is a subject of intensive research.

2. Scientific goals

The properties of concrete materials, including their durability, mainly depend on the structural factors and the interaction between micro- and macro-structure of the material. Cracks and losses are the two basic defects of the concrete structure, which may reduce the load-bearing capacity, leak tight integrity and stiffness of elements and structures, which in extreme cases may lead to failure and even building catastrophes. It is therefore important for the engineer designing the concrete mix to be familiar with the processes of damage and crack development in structural materials, especially those that are characterized by high brittleness. It allows improvement of the quality of concrete, from which the structures are made, estimation of defects and determination of their causes. This leads to obtaining composites with the highest durability and reliability.

The overall objective of the conducted scientific analyses was a description of fracture processes in concretes with the siliceous FA additive. Concretes with these additives have been used in the industry for approximately 80 years, and in the past two decades, their use in the composites with cement matrix has significantly increased. Therefore, it is obvious that in the course of such a long period of time, it managed to explore the effect on the basic physical and mechanical characteristics the siliceous FA additive, e.g. Sear Lindon (2001). However, based on literature research, it is clear that in this area of science, there is a clear gap. It is linked to the lack of complete data relating to the analysis of initiation and propagation of microcracks and cracks, in this type of materials, developing during the impact of complex states of stress on concrete. Siliceous FA is a pozzolanic material that demonstrates binding capacity through active FA ingredients (mainly SiO_2 and Al_2O_3) calcium hydroxide (Teixeira et. al., 2016). These reactions lead to the increase of C-S-H phase in concrete, which has a significant effect on the properties of concrete. Introduction of FA to the composition of cement causes changes in the phase composition and microstructure of cement paste, which is important in the development of mechanical parameters of concrete. Typically, composites with greater diversification of phases are characterized by higher sensitivity to the formation of local stress concentrations, which may imply the presence of damages and microracks in these locations. Such defects occur mainly in the areas of adjoining structures, and then, under the influence of increasing external loads, development, accumulation and consequently the premature material destruction occurs.

The reduction of strength of concrete results from initial structural defects existing inside material (Sadowski and Golewski, 2008). Moreover, one of the important issues that determine many properties of composites (including susceptibility to damage) are the types of coarse aggregates in the composition of concrete (Golewski and Sadowski, 2006). Cracks initiation and propagation in the concrete requires the knowledge of fracture mechanics parameters for all models of cracking. This is due to the fact that fracture is an important feature in concrete at all scales (Santosh and Gosh, 2015). Thus the three dimensional fracture process is generally complicated, i.e. an experimental estimation of all fracture mechanics parameters is extremely difficult and can be done for three separate fracture modes, such as:

- mode I, opening or tensile mode,
- mode II, sliding or in-plane shear (pure shear) mode,
- mode III, tearing or anti-plane shear mode.

Unfortunately, in the assessment of fracture toughness of concretes with FA the available results from experiments relate mainly to the first mode fracture and more rarely to the second mode. Fracture toughness under mode I – K_{Ic} and mode II – K_{IIc} for plain concretes containing siliceous FA additives, were reported in several articles (Lam et. al., 1998; Golewski and Sadowski, 2012; Golewski et. al., 2012; Golewski and Sadowski, 2014), while only one paper presents the values of the fracture toughness for the mode III – K_{IIIc} (Golewski and Sadowski, 2017). An additional problem is the fact that, all previous papers usually were related to the study of the fracture toughness of concrete containing very different content of FA (from 20 to 55 %) usually after 28 (and optionally after 56) days of their curing.

In this paper the reason encouraging the commencement of work on the analysis of the fracture processes in concretes with the siliceous FA additive was closely associated with the phenomenon of the variable dynamics of increasing the strength of such materials in the process of curing (Ganesh Babu and Siva Nageswara Rao, 1996). Due to the slow course of the pozzolanic reaction that has a direct influence on the mechanical properties of composites of this type, the increase in the strength at the initial stage of hardening is slow (Ganesh Babu and Siva Nageswara Rao, 1994). However, in the longer time of curing, compressive strength of cement with the FA reaches values exceeding the compressive strength of Portland cement of the same strength class.

In the present study in relation to the reason of working on this particular subject of the scientific paper, efforts were made to analyse the concrete at early age and in a period exceeding 28 days changes in compressive strength – f_{cm} and changes in fracture toughness of concretes. Fracture toughness tests were performed using basic, Mode I (tension at bending) according to the RILEM (1990). It should be added that the first microcracks in concrete composites are most often initiated by the occurrence of tensile stresses. Moreover, the three-point bending test of a notched specimen is the most common method of determining the fracture toughness of concrete, whereas K_{Ic} is the most important parameter of fracture toughness of concrete. Furthermore, as regards concrete, Mode I is of particular significance due to its low tensile resistance and high sensitivity to this type of stress.

Based on the above, during the tests were determined:

- the critical values of stress intensity factors – K_{Ic}^{S},
- the effect of age of concretes modified with the additive of the FA on analysed mechanical parameters.

All experiments were planned for two compositions of concrete mixture, with varying percentage of FA additive, which is often used in the cement industry. All tests were conducted for green concretes modified with the siliceous FA additive in the amount of 20% (FA-20) and 30% (FA-30) of weight of cement. The obtained results from experiments were compared to the values obtained for the reference concrete (FA-00), which was a composite made with the use of OPC, CEM I. For each of the 3 composites, all experimental tests were conducted in 6 time periods, with the age of concrete: 3, 7, 28, 90, 180 and 365 days.

3. Experimental program

3.1. Materials

3.1.1.Binder

In this investigation, both OPC and FA were used to form the binder of the concrete. Characteristic pictures of a typical grains, microstructures and dominant morphologies of OPC and FA particles was shown in (Golewski and Sadowski, 2014; Golewski, 2015; Golewski and Sadowski, 2017), whereas Fig. 1 shows the appearance of OPC and FA. Type I OPC was used while the FA was collected from a local thermal-electric power station. The chemical and physical properties of OPC and FA are shown in Tables 1 and 2.

3.1.2. Aggregates

Natural gravel of sizes between 2.0 and 8.0 mm were used as coarse aggregate. Pit sand between sizes 0–2 mm was used as fine aggregate. The physical properties of aggregates are shown in Table 3, whereas their particle size distribution in Table 4.

3.1.3. Water

The laboratory pipeline water free from contamination was used for all the mixes.

3.1.4. Plasticizer

A calcium lignosulfonate based plasticizer (P) was used in this study with a density of 1.16 g/cm^3 and the dosing range of 0.1÷1.0% of mass of cement. The plasticiser is used in an amount of 0.6% of mass of the binder.

3.2. Mix proportions

In this investigation, fixed: binder, sand, gravel, water and plasticizer contents of: 352, 676, 1205, 141 and 2 kg/m^3, respectively were used. The main variable in the mix design of the study was the amount of cement replacement with FA. The coal FA was used as partial cement replacement levels of: 0%, 20% and 30% for mixes with water-to-binder ratio (w/b) of 0.4. The mix proportions for all mixes are given in Table 5.

3.3. Mixing procedure

Both gravel and sand were dry mixed in a drum mixer for 2 min followed by addition of the binder materials (OPC and FA) which was further mixed for 3 min. Then, half of the mixing water was added for mixing of 2 min and followed by the remaining water and plasticizer. The cast specimens were covered with a polyurethane sheet and damped cloth. They were placed in 20±2°C chamber. After 2 days all specimens were demoulded. Then they were kept for the first 14 days in a chamber with a moisture-saturated atmosphere. During the next days to the study after: 28, 90, 180 and 365 days specimens were cured in laboratory conditions (20±2°C). In case of specimens tested after 3 and 7 days they were removed from the water at least a few hours before the study. After a suitable period of curing the compressive strength tests and fracture toughness tests were carried out.

3.4. Specimens used in the studies

When deciding about the number of specimens for experiments, attempts were made to reach a compromise between the cost of their preparation as well as the minimum amount necessary to guarantee reliable statistical values and the ability to generalise the results obtained from specimens on the entire population of concrete. Therefore, in all macroscopic tests, average values of the conducted experiments were assessed on the basis of results obtained for 6 specimens. Assortment of specimens for compressive strength and fracture toughness tests of concrete, for each of the mixtures in all time periods, was as follows:

- 6 cubic specimens (150 mm) for testing the compressive strength – f_{cm} ,
- 6 beams (80 x 150 x 700 mm) with one initial crack for testing fracture toughness under Mode I fracture – $K_{\mathrm{Ic}}^{\mathrm{S}}$; the dimensions of the specimens (Fig. 3) were selected based on the guidelines given in RILEM (1990).

3.5. Test method

3.5.1. Compressive strength

The uniaxial compression strengths were tested using a compression machine (Walter + Bai ag) with a maximum load of 3000 kN. The loading rate of compressive strength test was controlled between 0.5 MPa/s and 0.8 MPa/s. The compressive strengths were tested according to the standards of series EN 12390; exactly according to the standard EN 12390-3: 2011/AC:2012.

3.5.2. Fracture toughness

The testing of Mode I fracture toughness was performed according with the draft guidelines of RILEM recommendations (RILEM, 1990). To assess the fracture toughness of concrete, beams which had one initial centrally crack were used (see section 3.4). The beams were subjected to 3-point bending test, e.g. (Ho et. al., 2012). They were made in demountable bolted wooden forms. Preparation of the specimen was shown in Fig. 2. The assumed size of the initial crack in the beams was achieved by actually concreting flat steel plates, having a thickness of 3 mm (Fig. 2). The experiments were performed for the loading scheme presented in Fig. 3. Specimen dimensions in detail and exemplary crack paths, which were observed during experiment, were also shown in Fig. 3.

The tests setup apparatus is displayed in Fig. 4. Fig. 4a shows the whole of experimental stand from the side, whereas Fig. 4b on the front. All necessary results, needed to determine the critical stress intensity factors for concretes, were obtained with application MTS 810 testing machine (Fig. 4). The width of the initial crack opening during the tests was measured using a crack opening sensor that is the MTS clip gage axial extensometer, which was placed on the clamping test grips (Fig. 4).

The specimens placed in the experimental stand were subjected to cyclic loading process performed quasi statically. Loading rate was selected so that the maximum load was reached in approximately 5 min. The applied load was reduced at approximately 95% post-peak load. After reducing the load to 0 kN, the test specimen was loaded again. After that the cycles were repeated (6 to 8 times) until the beams were broken into 2 parts (Fig. 9). The whole cyclic deformation processes were described by the following curves: Force (*F*) – crack mouth opening displacement (*CMOD*) and *F* – displacement (*f*). The obtained results allowed for determination of the fracture toughness K_{Ic}^{S}, using the formula given in RILEM (1990).

4. Results and discussions

4.1. Conception of analysis of obtained test results

When compiling the results of strength and fracture toughness tests, tables for further analysis for each type of the conducted experiments included:

- the average values of $\overline{f}_{cm}$ and $\overline{K}_{Ic}^{S}$,
- statistic parameters such as standard deviation – δ and coefficient of variation – ν,
- maximum – max. and minimum – min. values obtained in the tests.

Furthermore, graphs presenting the summary of the given parameter for all series of concrete, in all time periods were prepared for average values in particular tests. The relationships of the analysed indicators as a function of the age of concrete were shown graphically in order to better illustrate the changes occurring in concretes during their curing. Percentage changes of parameters, during curing of composites, were also shown, taking the value obtained after 365 days as 100%.

4.2. Compressive strength

Table 6 summarises the results from compressive strength tests of concretes, for particular periods of curing, while Fig. 5 present relationships f_{cm}, as a function of the age of concretes. As expected, f_{cm} increased with age in all the concrete specimens. FA additive caused a clear decrease of compressive strength in concretes analysed at an early age, i.e. after 3 and 7 days. According to Table 6, value f_{cm} after 72 hours of curing was almost 8 and exactly 10 MPa higher in concrete without the FA additive in comparison to FA-20 and FA-30, respectively. After a week, the differences between the reference and modified concretes were only 3 MPa. According to Golewski and Sadowski (2012), in which a more detailed analysis of changes of strength parameters in concretes with the FA additive at a early age is presented, clear disproportions in the obtained results occur within 14 days of curing. After 3 weeks, 20% FA additive strengthens the structure of concrete composites to the extent that the values of f_{cm} are slightly higher in this type of concrete in comparison to FA-00. Also, after 28 days and in subsequent time periods, FA-20 had by far the highest strength, which was probably due to the sharp increase of pozzolanic reaction products after a longer time of curing. Concrete with a larger amount of FA was characterised by the lowest strength in the period up to 3 months. After a half year of curing, value of f_{cm} for this composite was higher in comparison to concrete without the additives, however, still lower in comparison to FA-20. A further increase of strength of FA-30 caused that after a year strength of this material was 4 MPa higher f_{cm} in comparison to FA-00 and lower by the same value in comparison to FA-20.

The conducted own tests have shown that compressive strength of concrete was increasing with time. The growth dynamics of this parameter, however, differed significantly in particular types of analysed composites. This can be easily observed by comparing relative changes of compressive strength over time, which is shown in Fig. 6.

After the first measurement, i.e. after 3 days, concrete FA-00 had more than 40% of the annual compressive strength, whereas in concretes with FA additives, this strength did not even had 30% of the final strength. After a week, concrete, without the FA additive, was characterised by a higher relative strength, however, in the analysis of obtained values, a clearer dynamics of strength increase in composites with FA was observed. Although reference concrete had already more than 50% of its 365 day strength, which was a result 10% better in relation to concretes with additives, a greater increase of f_{cm} was observed in concretes with FA between 3rd and 7th day of curing. Also, between 7th and 28th of curing, concretes with additives are characterised by significant increments of f_{cm} (amounting to: FA-20 – 50%, FA-30 – 62%). Clear growth trends of compressive strength, in modified composites, was observed even after 90 days after the start of tests. Both 20% and 30% FA additives caused increase of f_{cm} within 2 months by more than 20%, which was a result 6% better in relation to FA-00. After half a year in all types of composites, the increase of compressive strength was small and was approximately: 6% in FA-20, 7% in FA-30 and only 4% in the reference concrete. A similar trend was also observed in relation to one year concretes where the strength increase in concretes with FA was 7% and was higher by half in comparison to the results obtained for FA-00.

4.3. Fracture toughness

Table 7 summarises the results from fracture toughness $K_{\mathrm{Ic}}^{\mathrm{S}}$ of concretes, for particular periods of curing. Additionally, Fig. 7 present relationships $K_{\mathrm{Ic}}^{\mathrm{S}}$, as a function of the age of concretes.

Similarly as with the results from strength tests, values $K_{\mathrm{Ic}}^{\mathrm{S}}$ in the initial stages of curing of concretes were also very low. It was clearly seen in composites with FA additive, in which after 3 days, fracture toughness was 30% and 50% lower for FA-20 and FA-30, respectively, in comparison to the value obtained for FA-00. In subsequent time periods, for mature concretes, a sharp increase of fracture toughness occurred in concrete with 20% FA additive, for which values of $K_{\mathrm{Ic}}^{\mathrm{S}}$ clearly exceeded the results obtained for two remaining materials. Larger amount of micro-filler in the structure of concrete caused that FA-30 in the first 3 months clearly reached the lowest fracture toughness. However, in mature concretes the highest fracture toughness had FA-20 and FA-30 after 180 and 365 days.

Graph of relative changes $K_{\mathrm{Ic}}^{\mathrm{S}}$ shown in Fig. 8 is very similar to results presented for f_{cm} in Fig. 6. By comparing relative changes of fracture toughness in time under mode I fracture (Fig. 8), it can be concluded that the rate of increase of this parameter was highly dependent on the type of the analysed composite. As concrete FA-00 reached nearly 45% of the final value of $K_{\mathrm{Ic}}^{\mathrm{S}}$ after 3 days, subsequent increase of fracture toughness for this material was already quite stable. The 3-day values of $K_{\mathrm{Ic}}^{\mathrm{S}}$ with respect to 365-day values were 27% and 22% for FA-20 and FA-30, respectively. Also, after a week, large disproportions were noticed in the obtained results. The value of $K_{\mathrm{Ic}}^{\mathrm{S}}$ in concrete FA-00 accounted for almost 60% of the annual result. At the same time, in concretes with FA, fracture toughness was much less than 50% $K_{\mathrm{Ic}}^{\mathrm{S}}$ obtained for these concretes after 365 days. Sharp increase of $K_{\mathrm{Ic}}^{\mathrm{S}}$ for concretes with the FA additive was observed between 7th and 90th day of curing. During this time, fracture toughness for these materials increased by 79% for FA-20 and 89% for FA-30. In all of the analysed concretes, values $K_{\mathrm{Ic}}^{\mathrm{S}}$ after 180 days already reached more than 90% of annual results. Between the 90th and 365th day of curing, a clear increase of $K_{\mathrm{Ic}}^{\mathrm{S}}$ was observed only in concrete with 30% FA additive, Fig. 8.

Based on the results shown in Table 7 and Fig 7, it can be concluded that siliceous FA additive clearly changes fracture toughness of cement concretes under Mode I fracture. At early age, the structure of materials with these components significantly weakens. With the 20% FA additive, parameter $K_{\mathrm{Ic}}^{\mathrm{S}}$ after 3 days was 31% lower while after 7 days – 7% in relation to values obtained for FA-00. More evident change of fracture toughness resulted in an increase of the amount of the cement substitute in concrete by 10%. This resulted in a further decrease of $K_{\mathrm{Ic}}^{\mathrm{S}}$ by almost 20% in

3- and 7-day concretes in comparison to results for comparative concrete. Another analysis of $K_{\mathrm{Ic}}^{\mathrm{S}}$ already done for mature concrete also reflects the negative impact of 30% FA additive, but in relation to FA-20, it shows a completely different trend. 20% FA additive after a month of curing causes an increase in fracture toughness by 3%, while 30% additive – a clear drop of $K_{\mathrm{Ic}}^{\mathrm{S}}$ by 13%. This shows that after 28 days the 20% FA additive causes beneficial effects resulting from the pozzolanic reaction, whereas above this value there is still a decrease of mechanical parameters in modified concretes.

The analysis of fracture toughness in subsequent periods of time indicates that for 90-day concretes, another increase of $K_{\mathrm{Ic}}^{\mathrm{S}}$ in concretes with FA can be observed to the extent that the value of this parameter obtained for FA-20 is greater by 8% in relation to the value obtained for FA-00. When comparing the value of $K_{\mathrm{Ic}}^{\mathrm{S}}$ for the reference concrete and FA-30, it is concluded that $K_{\mathrm{Ic}}^{\mathrm{S}}$ is still greater in FA-00. However, the difference is slight and is only 4%. For concretes tested after: 180 and 365 days, beneficial effect of FA additive is in both smaller and larger percentage of its content. Fracture toughness in concretes with FA already exceeds the values obtained for FA-00/180 and FA-00/365 by 10% and 14% for FA-20/180 and FA-20/365 as well as 2% and 5% with respect to FA-30/180 and FA-30/365.

When comparing the effect of FA on fracture toughness (Table 7), and compressive strength of concretes (Table 6), distinct similarities in the effect of used mineral additives on the results obtained in both tests can be observed.

A view of the failured beams after tests is shown in Fig. 9. Fig. 9a shows a batch of fractured 6 specimens of one series, while Fig. 9b and 9c reveal specific details of beams with the zoom on cracked surface. The observed macroscopic types of cracks in particular composites may indicate a high strength of cement matrix in cured reference concretes as well as concretes with 20% FA additive and may indicate weak parameters of this phase for FA-20 and FA-30 after 3 and 7 days of curing.

5. Conclusions and practical tips

On the basis of fracture toughness tests, during Mode I loading, in which a portion of the binder was replaced with active pozzolanic siliceous FA, it can be concluded that:

1. It is possible to make sustainable green concrete with the addition of FA with high compressive strength and fracture toughness.
2. The FA additive in the amount of 20 and 30% of mass of cement significantly affects the change of compressive strength and fracture toughness in tension.
3. Obtained parameter values of f_{cm} and K_{Ic}^{S} depend on the age of concrete.
4. FA additive in the amount of up to 30% of mass of cement drastically reduced compressive strength and fracture toughness at early age.
5. 20% FA additive ensures high f_{cm} and K_{Ic}^{S} in matured concretes.
6. Concretes with 30% FA additive are characterized by highest dynamic increase of the parameters f_{cm} and K_{Ic}^{S}.
7. After 180 and 365 days, compressive strength and fracture toughness of FA-30 concrete is higher in comparison to the values obtained for reference concrete.
8. Results of the fracture toughness and the compressive strength are convergent qualitatively.

Green concretes with the siliceous FA additive are used in building structures – both cubature and industrial. Range of composites, made on the basis of the binders modified with this waste is very rich. Such concretes are used in construction industry: concrete, reinforced concrete and prestressed; in structures: monolithic, prefabricated, composite and prestressed. On the basis of the obtained results, several practical tips and recommendations on the use of sustainable concretes, with the siliceous FA, in concrete industry can be suggested:

1. In the case of concretes, which are scheduled for commissioning after 28 days, or later, the preferred solution is to use composites modified with the 20% FA additive.

2. The use of concretes with 30% FA additive in typical structures is possible, however, it should be taken into account that their strength and fracture toughness can be reduced for up to 6 months – compared to plain concretes.
3. It is not advisable to construct concrete structures, with the FA additive, if their commissioning is planned before the 28th day after the placing of concrete mixture.
4. It is not recommended to use composites with the FA additive in the prefabricated elements, in which the interoperational transport strength would be less than a week.
5. In any case, it is not advisable to use concretes with 20% and 30% FA additive, if they are subjected to any load in less than 3 days from the preparation of concrete mixture.

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References

Acharya P.K., Patro S.K., 2016. Use of ferrochrome ash (FCA) and lime dust in concrete preparation. J. Clean. Prod. 131, 237–246.

Aitcin P.C., 2000. Cements of yesterday and today. Concrete of tomorrow. Cem. Concr. Res. 30, 1349–1359.

Aprianti S E., 2017. A huge number of artificial waste material can be supplementary cementitious material (SCM) for concrete production – a review part II. J. Clean. Prod. 142, 4178–4194.

Blissett R.S., Rowson N.A., 2012. A review of the multi-component utilisation of coal fly ash. Fuel 97, 1–23.

Determination of fracture parameters (K_{Ic}^{S} and $CTOD_c$) of plain concrete using three-point bend tests., 1990. RILEM Draft Recommendations, TC 89-FMT Fracture Mechanics of Concrete Test Methods. Mater. Struct. 23, 457–460.

EPA, 2008. Study on Increasing the Usage of Recovered Mineral Components in Federally Funded Projects Involving Procurement of Cement or Concrete. Environmental Protection Agency, 2008.

Ganesh Babu K., Siva Nageswara Rao G., 1994. Early strength behaviour of fly ash concretes. Cem. Concr. Res. 24 (2), 277–284.

Ganesh Babu K., Siva Nageswara Rao G., 1996. Efficiency of fly ash in concrete with age. Cem. Concr. Res. 26 (3), 465–474.

Golewski G.L., 2015. Studies of natural radioactivity of concrete with siliceous fly ash addition. Cement Wapno Beton 2, 106–114.

Golewski G.L., Golewski P., Sadowski T., 2012. Numerical modeling crack propagation under Mode II fracture in plain concretes containing siliceous fly ash additive using XFEM method. Comput. Mater. Sci. 62, 75–78.

Golewski G.L., Sadowski T., 2014. An analysis of shear fracture toughness K_{IIc} and microstructure in concretes containing fly-ash. Constr. Build. Mater. 51, 207–214.

Golewski G.L., Sadowski T., 2012. Experimental investigation and numerical modelling fracture processes in fly ash concrete at early age. Sol. Stat. Phenom. 188, 158–163.

Golewski G., Sadowski T., 2006. Fracture toughness at shear (mode II) of concretes made of natural and broken aggregates. In: The Eight International Symposium on Brittle Matrix Composites, p. 537–546.

Golewski G.L., Sadowski T., 2017. The fracture toughness the K_{IIIc} of concretes with F fly ash (FA) additive. Constr. Build. Mater. 143, 444–454.

Gursel A.P., Maryman H., Ostertag C., 2016. A life-cycle approach to environmental, mechanical, and durability properties of “green” concrete mixes with rice husk ash. J. Clean. Prod. 112, 823e836.

Hemalatha T., Ramaswamy A., 2017. A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. J. Clean. Prod. 147, 546–559.

Ho A.C., Turatsinze A., Hameed R., Vu D.C., 2012. Effects of rubber aggregates from grinded used tyres on the concrete resistance to cracking. J. Clean. Prod. 23, 209–215.

Jayapalan A.R., Lee B.Y., 2013. Can nanotechnology be ‘green’? Comparing efficacy of nano and microparticles in cementitious materials. Cem. Concr. Compos. 36, 16–24.

Keun-Hyeok Y., 2013. Assessment of CO_2 reduction of alkali-activated concrete. J. Clean. Prod. 39, 265–272.

Kotwica Ł., Pichór W., Kapeludszna E., Różycka A., 2017. Utilization of waste expanded perlite as New effective supplementary cementitious material. J. Clean. Prod. 140, 1344–1352.

Kurdowski, W., 2014. Cement and Concrete Chemistry. Springer Netherlands, New York.

Lam L., Wong Y.L., Poon C.S., 1998. Effect of fly ash and silica fume on compressive and fracture behaviors of concrete. Cem. Concr. Res. 28, 271–283.

Long G., Gao Y., Xie Y., 2015. Designing more sustainable and greener self-compacting concrete. Const. Build. Mater. 84, 301–306.

Lothenbach B., Scrivener K., Hooton R.D., 2011. Supplementary cementitious materials. Cem. Concr. Res. 41, 1244–1256.

Mehta P.K., 2002. Greening of the concrete industry for sustainable development. Concr. Inter. (July), 23–28.

Mehta P.K., 2001. Reducing the environmental impact of concrete. Concr. Inter. (October), 61–66.

Meyer C., 2009. The greening of the concrete industry. Cem. Concr. Compos. 31, 601–605.

Mo K.H., Alengaram U.J., Jumaat M.Z., Yap S.P., Lee S.C., 2016. Green concrete partially coprised of farming waste residues: a review. J. Clean. Prod. 117, 122–138.

Nagaratnam B.H., Rahman M.E., Mirasa A.K., Mannan M.A., Lame S.O., 2016. Workability and heat of hydration of self-compacting concrete incorporating agro-industrial waste. J. Clean. Prod. 112, 882–894.

Paris J.M., Roessler J.G., Ferraro C.C., DeFord H.D., Townsend T.G., 2016. A review of waste products utilized as supplements to Portland cement in concrete. J. Clean. Prod. 121, 1–18.

Sadowski T., Golewski G., 2008. Effect of aggregate kind and graining on modelling of plain concrete under compression. Comput. Mater. Sci. 43 (1), 119–126.

Santosh M., Ghosh M.A., 2015. Multi-scale identification of concrete material parameters. Theor. App. Fract. Mech. 75, 8–15.

Sear Lindon K.A., 2001. Properties and use of coal fly ash. A valuable industrial by-product. Thomas Telford Ltd, London.

Teixeira E.R., Mateus R., Camoes A.F., Braganca L., Branco F.G., 2016. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. J. Clean. Prod. 112, 2221–2230.

Thatcher A., Milner K., 2016. Is a green building really better for building occupants? A longitudinal evaluation. Build. Environ. 108, 194–206.

Vargas J., Halog A., 2015. Effective carbon emission reductions from using upgraded fly ash in the cement industry. J. Clean. Prod. 103, 948–959.

Yang K.-H., Jung Y.-B., Cho, M.-S., Tae S.-H., 2016. Effect of supplementary cementitious materials on reduction of CO_2 emissions from concrete. J. Clean. Prod. 112, 4041–4052.

Highlights

Determination of the fracture toughness $K_{\mathrm{Ic}}^{\mathrm{S}}$ and compressive strength f_{cm} in green concretes containing fly ash.

The influence of curing time was analysed.

Changes in values of f_{cm} and $K_{\mathrm{Ic}}^{\mathrm{S}}$ between 3rd and 365th day were examined.

Cracked surfaces were assessed.

Practical tips and recommendations are given.

Figure captions

Fig. 1. Apperance of OPC and FA.

Fig. 2. Specimen for mode I fracture tests during preparation; 1-wodeen form, 2-concrete beam, 3-steel plate.

Fig. 3. Specimen with: a) static scheme, b) geometry, c) exemplary crack paths, d) blunted notch, e) details of caliper gauge; a_0-height of initial crack, HO-caliper gauge holder thickness, CMOD-crack mouth opening displacement.

Fig. 4. Testing setup: a) from the side, b) on the front; 1-specimen, 2-MTS 810 press 3-system applying force onto the specimen, 4-axial clip gage extensometer, 5-clamping test grips, 6-supporting system, 7-initial crack (dimensions in mm).

Fig. 5. Effect of the FA content on the compressive strengths.

Fig. 6. Relative changes of compressive strengths over time.

Fig. 7. Effect of the FA content on the fracture toughness.

Fig. 8. Relative changes of fracture toughness over time.

Fig. 9. View of beams after conducted tests: a) batch of beams, b) details of beams, c) zoom on cracked surface; 1-beam, 2-cracked surface, 3-place in which the steel plate was inserted.

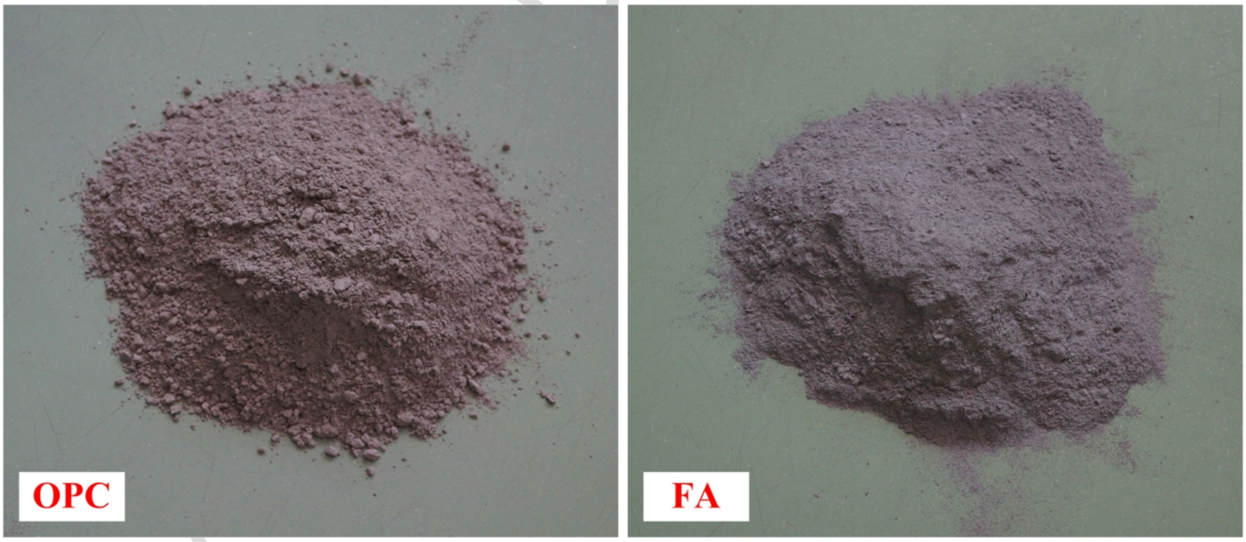
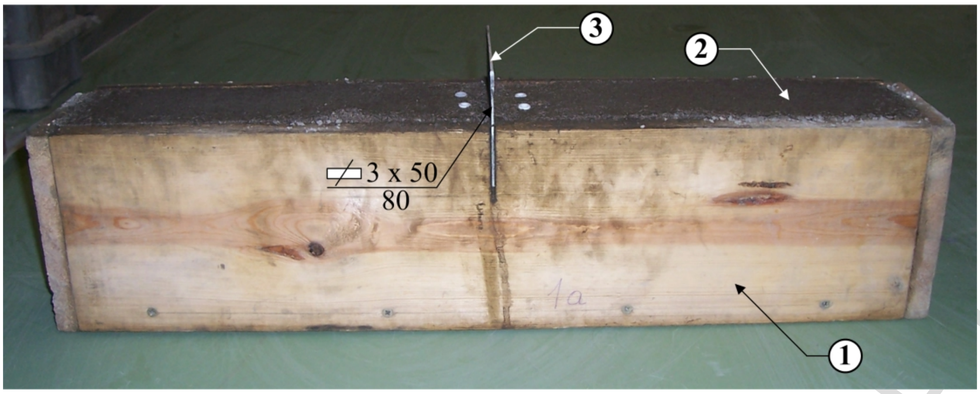


Fig. 1.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2
3 x 50
80
1

Fig. 2.

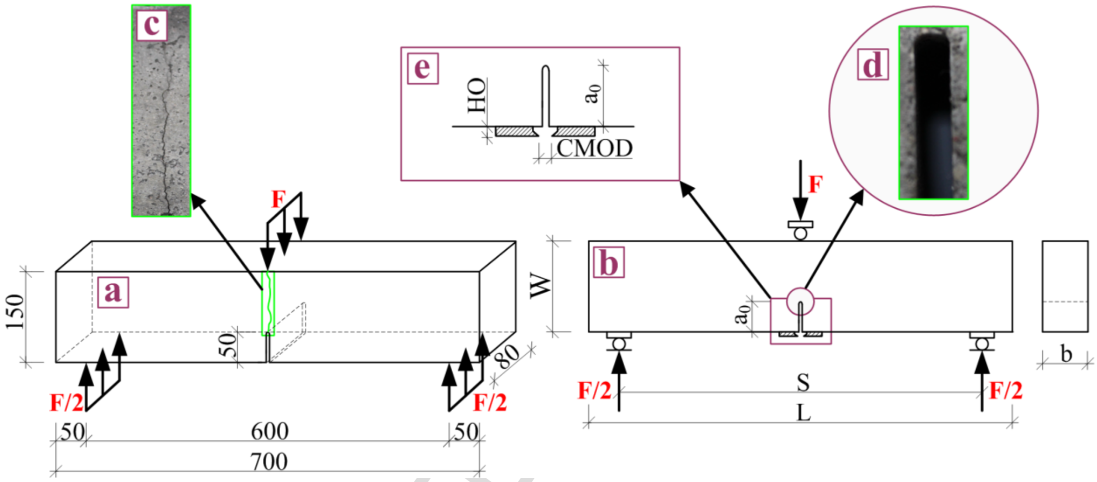
c
e
HO
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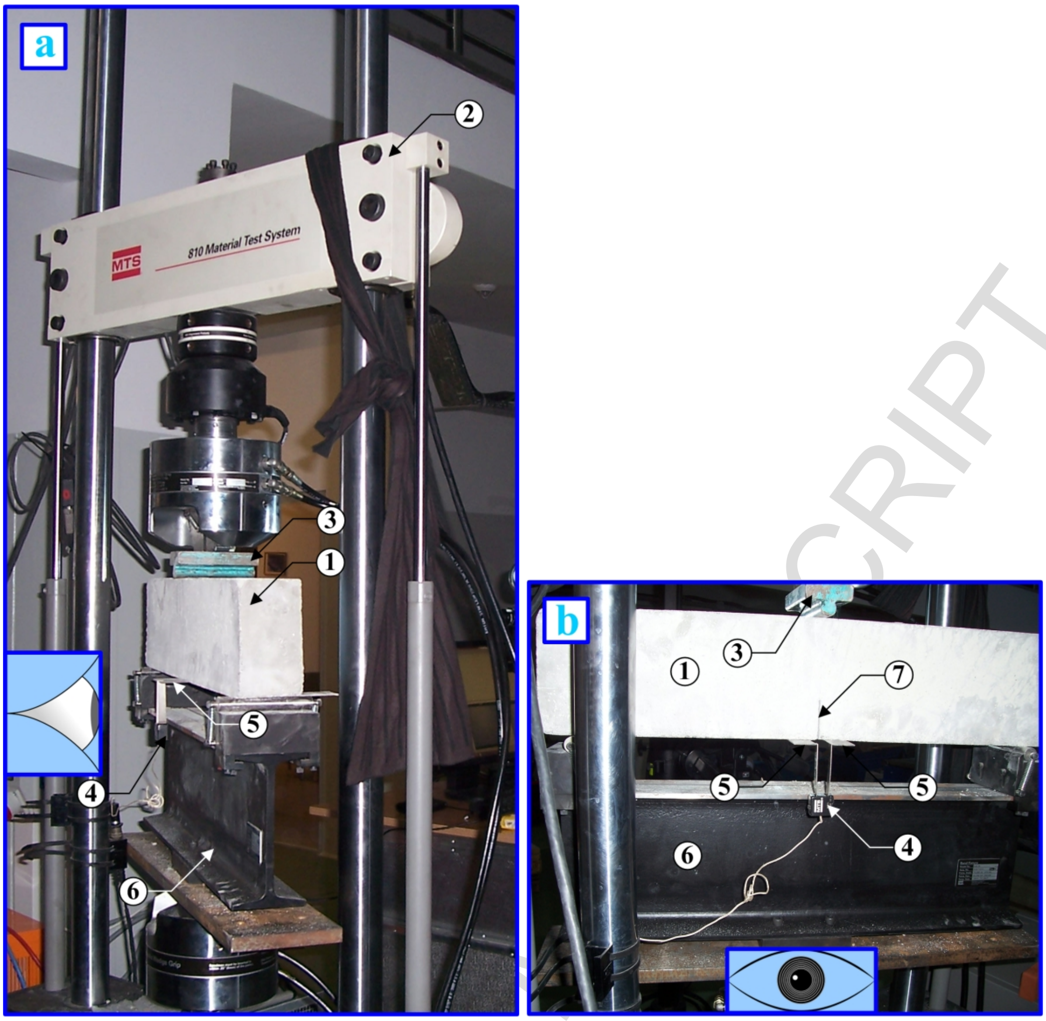
Fig.3.


a
810 Material Test System
MTS
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1
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4
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b
3
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4
6

Fig. 4.

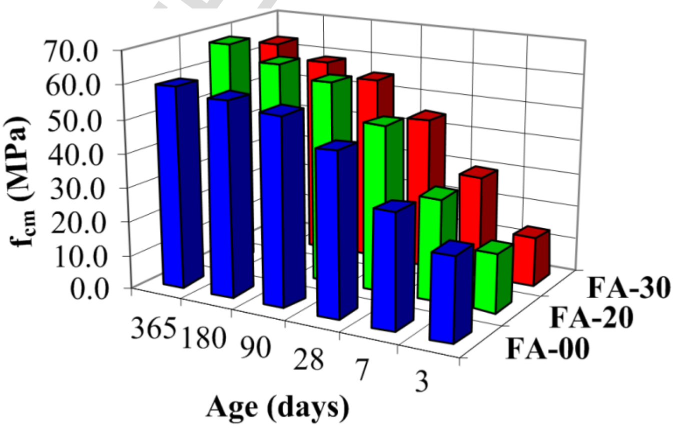
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
f_{cm} (MPa)
365
180
90
28
7
3
Age (days)
FA-30
FA-20
FA-00

Fig. 5.

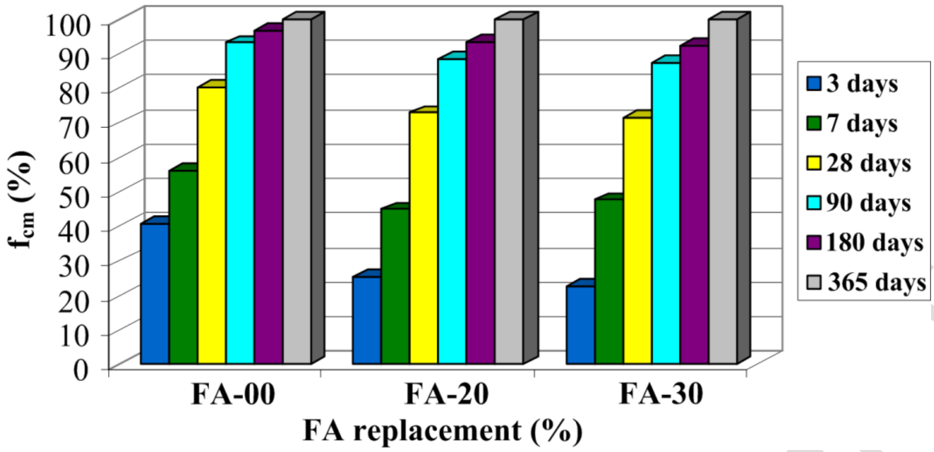

Fig. 6.

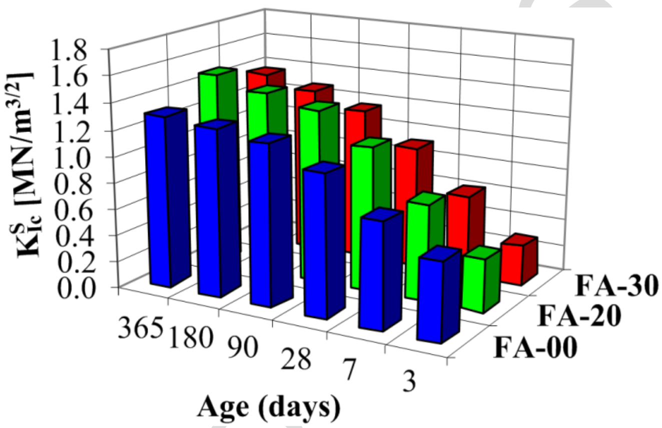

Fig. 7.

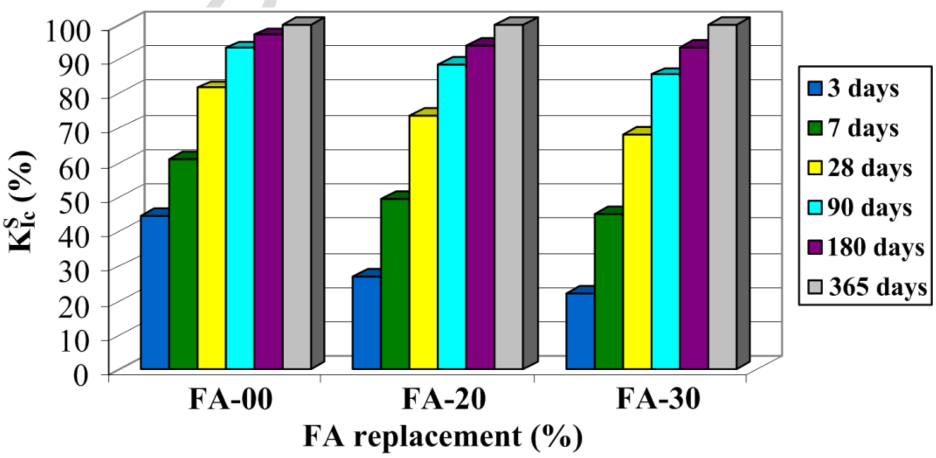

Fig. 8.

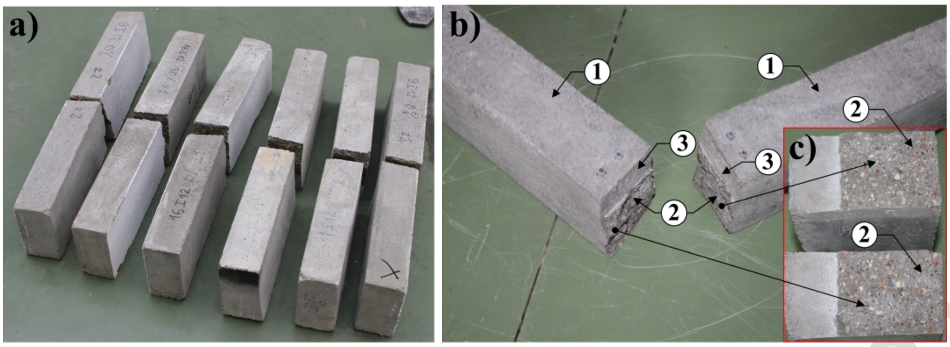

Fig. 9.

Tables

Table 1 – Chemical composition of OPC and FA (% by weight).

Chemical composition	FA	OPC
SiO_2	50.96	21.37
Al_2O_3	25.88	5.02
Fe_2O_3	8.25	2.40
CaO	2.15	63.95
Na_2O	1.26	0.18
K_2O	2.65	0.91
SO_3	0.65	3.00
MgO	2.60	2.47
P_2O_5	0.35	–
Cs_2O	0.09	–
BaO	0.32	–
TiO_2	1.36	–
Cl	–	0.06

Table 2 – Physical properties of OPC and FA.

Properties	FA	OPC
Specific gravity (g/cm^3)	2.14	3.11
Specific surface area (cm^2/g)	3640	3280
Loss on ignition (%)	3.20	1.24
Apperance	Dark grey	Light grey

Table 3 Physical properties of sand and gravel.

Property	Unit	Aggregate type	
		Sand	Gravel
Specific density	(g/cm^3)	2.60	2.65
Bulk density	(g/cm^3)	2.20	2.25
Compressive strength	(MPa)	33	34
Modulus of elasticity	(10^2MPa)	330	330
Sand point for mix	(%)	40.7	

Table 4 – The particle size distribution of the aggregates used.

Fraction (mm)	Content of aggregates fraction (%)		
	Sand	Gravel	Mix
0÷0.125	2.9	0.7	1.7
0.125÷0.25	14.8	0.4	5.6
0.25÷0.5	41.1	0.4	15.3
0.5÷1.0	32.7	1.6	12.4
1.0÷2.0	4.5	6.9	5.7
2.0÷4.0	4.0	19.9	13.9
4.0÷8.0	0.0	63.1	40.2
8.0÷16.0	0.0	7.0	5.2
Sand point	96.0	10.0	40.7

Table 5 – Mix proportions of concrete (kg/m³).

Mix	Cement	FA	Water	P	Sand	Gravel
FA-00	352	0	141	2	676	1205
FA-20	282	70	141	2	676	1205
FA-30	246	106	141	2	676	1205

Table 6 – Compressive strengths results.

Mix	Age (days)	$\overline{f}_{cm}$ (MPa)	δ (MPa)	ν (%)	f_c, max. (MPa)	f_c, min. (MPa)
FA-00	3	24.23	2.60	10.73	26.86	21.11
	7	33.18	2.57	7.74	35.42	30.71
	28	47.51	2.55	4.58	49.24	45.97
	90	55.13	2.51	4.55	57.02	53.18
	180	57.22	2.48	4.33	59.64	55.34
	365	59.25	2.46	4.15	61.43	57.79
FA-20	3	16.95	3.05	17.99	19.62	13.53
	7	30.12	3.03	10.06	26.84	33.15
	28	48.96	3.02	6.17	50.25	46.89
	90	59.35	2.80	4.72	61.21	58.65
	180	62.81	2.52	4.01	64.04	60.68
	365	67.29	2.35	3.49	69.32	66.13
FA-30	3	14.23	3.59	25.23	16.95	11.66
	7	30.06	3.57	11.88	32.28	27.84
	28	45.10	3.55	7.87	47.01	42.93
	90	55.11	3.10	5.63	56.72	53.49
	180	58.83	2.86	4.86	60.23	57.12
	365	63.27	2.50	3.95	65.31	62.09

Table 7 – Fracture toughness results.

Mix	Age (days)	$\bar{K}_{Ic}^{S}$ (MN/m$^{3/2}$)	δ (MN/m$^{3/2}$)	ν (%)	K_{Ic}^{S}, max. (MN/m$^{3/2}$)	K_{Ic}^{S}, min. (MN/m$^{3/2}$)
FA-00	3	0.58	0.08	13.79	0.92	0.36
	7	0.79	0.09	11.39	1.14	0.57
	28	1.06	0.10	9.43	1.30	0.91
	90	1.21	0.08	6.61	1.49	1.02
	180	1.26	0.06	4.76	1.53	1.04
	365	1.30	0.05	3.85	1.51	1.10
FA-20	3	0.40	0.09	22.50	0.95	0.19
	7	0.73	0.09	12.33	1.02	0.60
	28	1.09	0.11	10.09	1.39	0.97
	90	1.31	0.10	7.63	1.52	0.99
	180	1.39	0.07	5.04	1.58	1.01
	365	1.48	0.06	4.05	1.62	1.07
FA-30	3	0.30	0.08	26.67	1.02	0.16
	7	0.62	0.08	12.90	1.22	0.36
	28	0.93	0.10	10.75	1.28	0.61
	90	1.17	0.09	7.69	1.43	0.98
	180	1.28	0.08	6.25	1.50	1.00
	365	1.37	0.07	5.11	1.61	1.01