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Determination of fracture toughness in concretes containing siliceous fly ash during mode III loading

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Abstract. This paper describes laboratory tests carried out to evaluate the influence of class F fly ash (FA) on fracture toughness of plain concretes, specified at the third model fracture. Composites with the additives of: 0%, 20% and 30% siliceous FA were analysed. Fracture toughness tests were performed on axial torsional machine MTS 809 Axial/Torsional Test System, using the cylindrical specimens with dimensions of 150/300 mm, having an initial circumferential notch made in the half-height of cylinders. The studies examined effect of FA additive on the critical stress intensity factor K_{IIIc}. In order to determine the fracture toughness K_{IIIc} a special device was manufactured.The analysis of the results revealed that a 20% FA additive causes increase in K_{IIIc}, while a 30% FA additive causes decrease in fracture toughness. Furthermore, it was observed that the results obtained during fracture toughness tests are convergent with the values of the compression strength tests.

Keywords: concrete; siliceous fly ash; fracture toughness, third model fracture

1. Introduction

1.1 The advantages of fly ash and their applications in concrete composites

Acquisition of natural raw materials and fuels for the economy in Poland and in the world is becoming an increasing problem. The branches of economics that consume a lot of energy and raw materials include the construction materials industry, especially the cement and concrete industry. Therefore, a very important issue is to find cheap and fully useful materials of mineral origin that will be able to replace the most expensive component in the composition of cement, which is the Portland cement clinker.

One of these materials is siliceous Fly Ash (FA) which is a by-product obtained in the process of hard coal combustion performed in electric power stations and in thermal-electric power stations (Ahmaruzzaman 2010). 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. Moreover, siliceous FA, used as an additive to concrete as cement replacement in amount up to 30%, has no special effect on the radioactivity indexes (Golewski 2015). Replacement of part of cement by the FA has significant financial benefits because the FA is a much less expensive material in comparison to Portland cement clinker, from which the Portland cement is produced.

Based on the above, nowadays the FA is probably the most frequently used pozzolanic waste material in cement and concrete production worldwide, mainly because it is available in large amounts for low price. Therefore the FA is a subject of intensive research. Nowadays, a good quality siliceous FA is used for production of Portland-composite cement and plain concretes as well as: concretes with higher strengths – inc. high performance concretes (Poon *et al.* 2000) and ultra-high performance concretes (Yu *et al.* 2015), self-compacting concretes (SCC)–inc. SCC with low volume FA (Siddique 2011), SCC with high volume FA (Sahmaran *et al.* 2009) and steel fiber reinforced SCC (Aslani 2013, Aslani and Natoori 2013, Aslani and Samali 2014, Aslani and Nejadi 2014). Siliceous FA are also used to produce other types of concrete composites, e.g., composites with hybrid binders (Lam *et.al.* 1998, Zhang and Li 2013, Rathish Kumar *et al.* 2014, Zhang *et al.* 2016) and materials, e.g., mud fly ash brick masonry (Nazar and Sinha 2006). The implementation of the FA into these composites influences properties not only of the concrete mixture but also of the hardened concrete. Advantageous impact of the FA addition in concretes is

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related to: morphology of its particles, pozzolanic activity and microfiller effect. Additionally, concrete with fly ash is characterised by advantageous applicable qualities and has important effect in strength of concrete (Liu and Wang 2011). For these reasons the FA is also used in various applications e.g.: transforming siliceous FA into a zeolitic material (Ahmaruzzaman 2010), to produce glass ceramics (Cheng and Chen 2004) or as a admixture of the cement paste for electromagnetic interface shielding (EMI shielding) (Cao and Chung 2004). An interesting and important use of the FA in the composite materials industry is application of these wastes in the synthesis of carbon nanomaterials such as: nanotubes, nanofibers or graphene (Nasibulin *et al.* 2013). These waste materials are also particularly useful in environment protection, e.g.: as the adsorbents of harmful compounds, or as components of cement binders used for the immobilization of heavy metals (Giergiczny and Król 2008). The wide range of applications of modified FA additives is also related to the high resistance of this type of concretes to many corrosive factors. The beneficial effect of this type of additive was shown in the tests analyzing the impact of exposure of aggressive factors on the concrete itself (Zuguan *et al.* 2007) as well as the reinforcement in reinforced concrete elements (Malhotra *et al.* 2000).

1.2 An analysis of fracture processes in concrete at complex loading

Failure of concrete is a multi-stage process that is conditioned by level and type of applied external loads as well as by internal structure of composite (Xia *et al.* 2012). The reduction of strength of concrete results from initial structural defects existing inside material (Golewski and Sadowski 2006, Sadowski and Golewski 2008). According to the Jacobsen *et al.* (2013), an important issue in the modeling of the fracture processes in concrete is a description of the topography of the crack surface. Additionally, a crucial role on the fracture bahaviour of concrete plays an aggregate structure (Golewski and Sadowski 2006, Monteiro Azevedo and Lemos 2006).

On the other hand a description of the processes of cracks initiation and propagation in a material requires the knowledge of all fracture mechanics parameters, i.e.: K_{Ic}, K_{IIc} and K_{IIIc} (Sadowski and Golewski 2008). This is due to the fact that fracture is an important feature in concrete at all scales (Santosh and Ghosh 2015) and furthermore the cracks in real structural elements usually start to initiate in the mixed mode: I-II loading (Di Prisco *et al.* 2000), I-III loading (Lo *et al.* 2002) or I-II-III loading (Song *et al.* 2004). Moreover, based on the Meyer and Peng (1997) the damage of concrete subjected to complex loading involves strong anisotropy due to its highly heterogeneous nature and the geometrically anisotropic characteristic of the microcracks.

In practice, different approaches are used for the modeling of fracture processes in concrete. Also meso-mechanical models (Sadowski and Golewski 2008) and fractal models (Konkol and Pokropski 2007), based on knowledge of internal structure of concrete, are very effecive. In recent years, with the development of computer techniques, are frequently used numerical simulations. Numerical methods may be based on Finite Element Method (Huang and Huang 2011) as well as Meshless Method (Ghosh and Chaundhuri 2013). New possibilities in the analysis of fracture processes also gives Extended Finite Element Method (X-FEM). X-FEM method enables numerical modelling of defect initiation and development during deformation process in three dimensional (3D) space. All stages of the crack growth, starting from initiation to the specimen failure, can be analysed in this method (Golewski *et al.* 2012).

2. Purpose and scope of the present study

Up till now the effect of FA influence on the fracture toughness of the concrete composites was not investigated systematically. Such studies was carried out rather rarely. Fracture toughness under Mode I for plain and high performance concretes containing siliceous FA studied: Lam *et al.* (1998), Bharatkumar *et al.* (2005), Vejmelkova *et al.* (2009), Golewski and Sadowski (2016). Golewski and Sadowski (2014), presents the values of the fracture toughness for the Mode II (K_{IIc}) for plain concretes and modified concretes with the 10%, 20% and 30% class F FA additives. The tests done on Compact Shear Specimens showed that the 10% and 20% FA additive cause the increase of the K_{IIc} by 1.9% and 3.5%. The replacement of a portion of cement with the 30% FA additive reduces the K_{IIc} by 13.9%. The results obtained in experimental studies were also confirmed numerically by analysis of the 3D fracture processes, using X-FEM method and ABAQUS program. Clear convergence of experimental results with numerical calculations have been observed both in the young concrete (Golewski and Sadowski 2012) and mature concrete (Golewski *et al.* 2012).

Investigations of the fracture toughness at Mode III for different types of materials has been carried out since the 80s of the last century for: ceramic materials (Suresh and Tschegg 1987), steel alloys (Reardon and Quesnel 1995), wooden materials (Ehart *et al.* 1998) and piezoelectric materials (Qin 2005). The first and probably only available in the literature results of fracture toughness tests of concretes at the Mode III fracture were presented by Bazant and Prat (1988), Bazant *et al.* (1990). Up to the author knowledge there are no studies on fracture toughness in the Mode III for the concretes with the FA additive.

Therefore this paper provides a new test method and new experimental results concerning K_{IIIc} in the analysed concretes. The importance of the fracture toughness in the antiplane shear (Bazant *et al.* 1990) is particularly visible in the analysis of structures subjected to torsion such as: slabs, beams bent in the plan, end-beams in ceilings, balcony slab ring beams, girders of spatial frames, spiral stars, crane beams, T-beams and other. Selected examples of reinforced ad prestressed concrete elements in which torsion occurs was shown by Kamiński and Pawlak (2011) and Rahal (2001). An analysis of reinforced concrete elements subjected to torque is important especially in the state II of construction, i.e., cracked phase. In this case torsional

Table 1 Chemical composition of the OPC and the FA (mass %)

Component	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	LOI	C_3S	C_2S	C_3A	C_4AF
OPC	21.37	5.02	63.95	2.47	3.0	2.4	1.24	60.69	15.82	9.24	7.28
FA	50.96	25.88	2.15	2.6	0.65	8.25	3.2	-	-	-	-

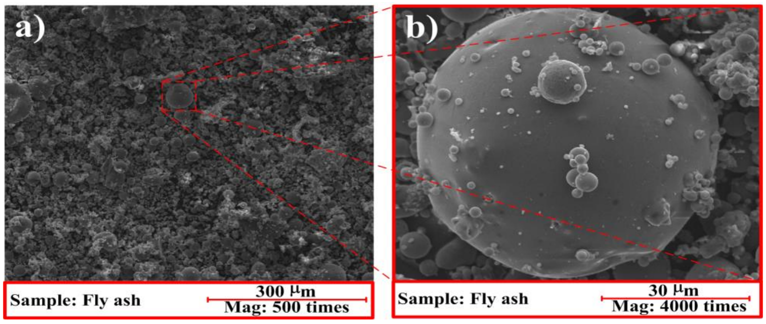

Fig. 1 Microstructures and grains of used FA: (a) grains (Magnification: 500 times), (b) grain with cenospheres (Magnification: 4000 times)

forces load to a much larger loss of stiffness in state II, due to the strong cracking, than the loss of flexural stiffness (Lopes *et al.* 2014).

In particular, the paper contains the comparative analysis of the fracture toughness K_{IIIc} of the plain concretes and those ones modified by the siliceous FA additive. The experiments were done with the same concretes composition tested earlier in the Mode II fracture (Golewski and Sadowski 2012, Golewski *et al.* 2012, Golewski and Sadowski 2014). It was found, that 10% siliceous FA additive slightly affects the value of the parameter K_{IIc} causing its increase by only 1%, whereas 20% and 30% FA additives significantly change the fracture toughness of concrete. 20% siliceous FA additive affects the increase of fracture toughness of concrete by a few percent, while replacement of the cement in the concrete mix with larger quantity of the FA decreases the K_{IIc} more than 10% (Golewski and Sadowski 2014).

In this paper the fracture toughness tests to estimate critical stress intensity factor–K_{IIIc} and the compressive strength tests were conducted with three types of concretes of different amount of the siliceous FA additive:

- without the FA additive – FA-00,
- with 20% FA additive – FA-20,
- with 30% FA additive – FA-30.

3. Materials and experimental programm

3.1 Materials

In this study, the following materials were used for making the mixtures: Ordinary Portland Cement (OPC) CEM I 32.5 *R* from Chełm cement plant, with the compressive strength equal to 23.3 MPa in the age of 2 days and 50 MPa after 28 days of curing, natural gravel aggregates of maximum grain size up to 8 mm (from Las Suwalski deposit), a pit sand from Markuszów deposit, siliceous (class *F*) FA and a plasticizer (0.6% of binding material weight). The class *F* FA is a result of energetic combustion of hard coal in the Puławy thermal-electric power station. The chemical constituents of the OPC and the FA are shown in Table 1. The FA is a class *F* with 85.09% of $SiO_2 + Al_2O_3 + Fe_2O_3$, 0.65% of SO_3 and 3.2% of Loss of Ignition (LOI) meeting the requirement of ASTM C618.

The microstructural testing of the FA was carried out using a QUANTA FEG 250 at magnification from 200 to 80.000 times equipped with an energy dispersive Spectroscopy (EDS EDAX). Fig. 1 presents characteristic pictures of a typical grains and microstructures of used FA at various magnifications. The pictures show very small finess of the FA (a few to 50 μm) and characteristic cenospheres. The Blaine fineness of the OPC and the FA are 3300 and 3600 cm^2/g. The specific gravities of the OPC and the FA are 3.11 and 2.14 respectively. Physical properties of the OPC and the FA (Table 1), and Fig. 1 suggest that the FA is finest, followed by the OPC. Small particle size of the FA has a beneficial effect on compressive strength, durability and permeability of concretes with these additives and is helpful in improving the transition zone characteristics through processes of pore refinement and grain refinement (Mehta and Monteiro 1987).

Strength activity index tests of the FA carried out in accordance with the EN 450-1 standard indicated that this activity is: after 28 days-92%, while after 90 days-111%. The high activity of the used FA can also be indicated by its small particle size, which was observed in physical properties and SEM studies (Fig. 1).

The crystalline phases of the FA were identified by XRD patterns. XRD graph were obtained by a PANalytical X'Pert PRO MPD diffractometer (with the PW 3050 goniometer), Cu lamp, and graphite monochromator. The diffractogram from 5° to 65° in the 2θ and scanning rate was at 0.05° intervals. PANalytical X’Pert HighScore and the ClayLab ver. 1.0 software were used to process difraction data. The identification of mineral phases was based on the PCPPDFWIN ver. 2.1 database formalized by the JCPDS-ICDD. The X-ray diffractogram of the FA (Fig. 2) shows that there are, beside glass, four major crystalline components in the phase composition of the FA: quartz

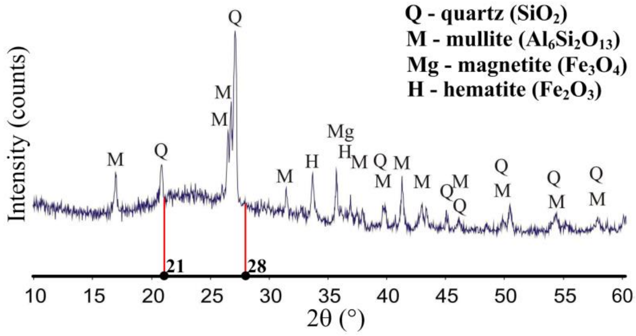

Fig. 2 XRD pattern of the Fly ash

Table 2 Mix proprtions of the concrete composites (kg/m^3)

Concrete	OPC	FA	Water	Sand	Coarse aggregate	Plasticizer
FA-00	352	0	141	676	1205	2
FA-20	282	70	141	676	1205	2
FA-30	246	106	141	676	1205	2

(SiO_2), mullite ($Al_6Si_2O_{13}$), magnetite (Fe_3O_4) and hematite (Fe_2O_3).

On the diffractogram, a characteristic increase in intensity at the angle ranging from 21-28° 2θ can be observed as well as relatively low intensity of the peaks of quartz and mullite phases. This image of the phase composition of the FA indicates their fine particle size and a high strength activity index.

A glass phases content and crystalline phases content in siliceous FA was investigated by the Rietvield quantitative analysis. The glass content in FA was 71.5%. The contents of the remaining phases determined by Rietveld analysis was: quartz–19.7% and mullite–8.8%.

3.2 Mix proportions and specimen preparation

The methodology used for determining the composition of the mixtures consisted in replacing a suitable amount of cement volume (weight volume content) in the mixture with a corresponding amount of the FA to ensure that the total amount of binding material is always constant. Experiments of concrete with a similar amount of additives were described by Zuguan *et al.* (2007).

The mix proportion of the concrete compositions are given in Table 2. All mixtures had the same water-binding material indicator w/B=0.4. The cast specimens were covered with polyurethane sheet and damped cloth and placed in 20±2℃ chamber. All specimens were demoulded at the age of 2 days. Then they were kept for 14 days in a chamber with a moisture-saturated atmosphere and for another 14 days under laboratory conditions (20±2℃). After 28 days of curing the compressive strength tests and other basic tests were carried out. In order to decrease the dispersion of the test data, 6 specimens were prepared for each mixture (both in the test of the compressive strength and fracture toughness).

3.3 Compressive strength analysis

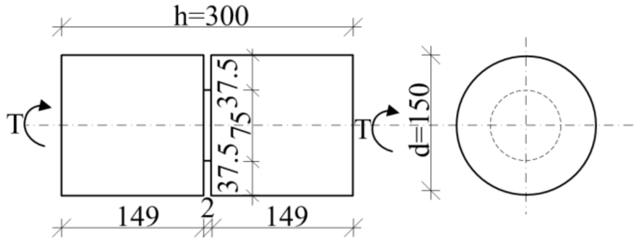

Fig. 3 Geometrical configuration of tested specimen (dimensions in mm), T-torque

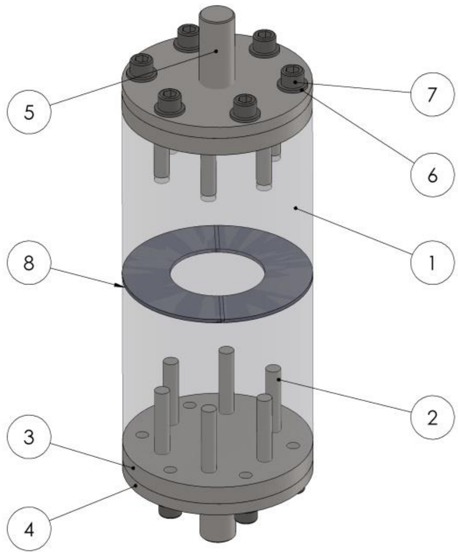

Fig. 4 The Device for fracture toughness test in the Mode III fracture: 1-concrete specimen, 2-bolt M12/65, 3-bottom plate, 4-top plate, 5-bolt M28/70, 6-washers, 7-bolt M12/20, 8-insert

The uniaxial compression strengths were tested using a compression machine (Walter+Bai ag) with a maximum load of 3000 kN. The compressive strengths (f_{cm}) were tested with application of cubic specimens (150 mm) according to the standards of series EN 12390. The loading rate of compressive strength test was controlled between 0.5 MPa/s and 0.8 MPa /s.

3.4 Test setup and method of the mode III fracture

3.4.1 Specimens

In order to determine the fracture toughness K_{IIIc}, cylindrical specimens with a diameter of 150 mm and a height of 300 mm having an initial circumferential notch of 2 mm thickness were tested (Bazant and Prat 1988, Bazant *et al.* 1990). Initial notch depth was equal to ¼ of the diameter of the cylinders. Initial notches in the specimens were created during their formation by application of the two semi-circular steel inserts placed in the half-height of specially prepared cylindrical forms. Geometrical configuration of tested specimen is shown in Fig. 3.

3.4.2 The device for the fracture toughness test

The Device for the fracture toughness test at the Mode III fracture consisted of the cylindrical specimen with the

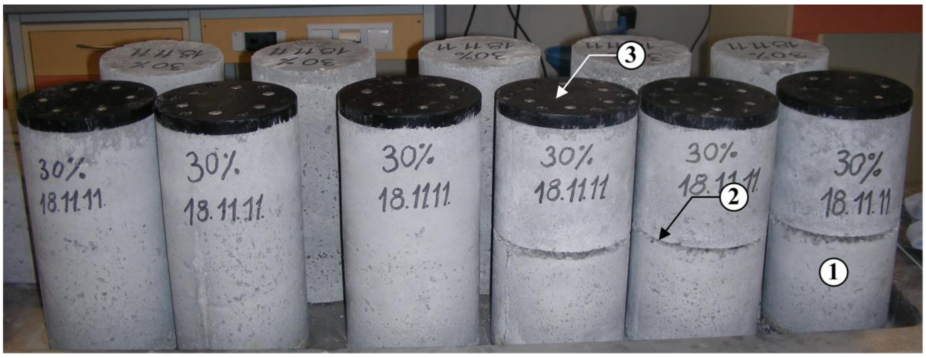

Fig. 5 A group of devices prepared to fracture toughness tests: 1-concrete specimen, 2-initial crack 3-concreted bottom plate

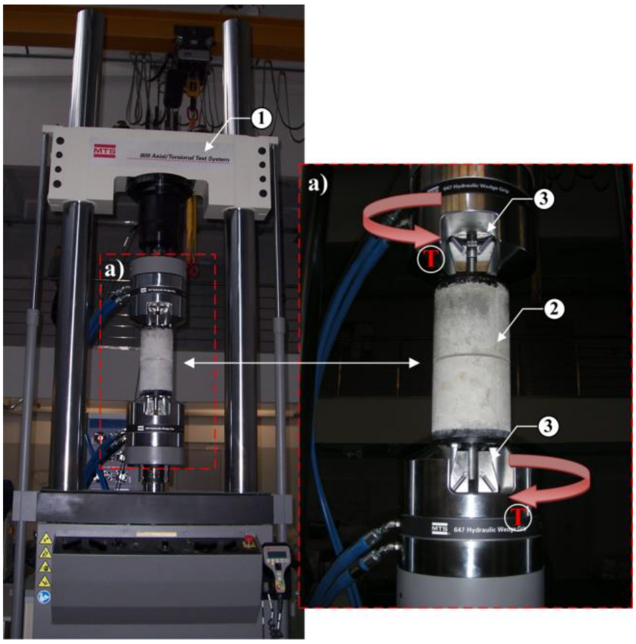

Fig. 6 The experimental stand with the fixed specimen subjected to torsion: a) a detail of the mounting device for testing of the fracture toughness; 1-MTS 809 press, 2-device for testing of the fracture toughness, 3-the grips of the press, *T*-torque

formed initial crack (Fig. 3), steel plates, and screws with washers securing the specimen in the press holders. To mount the specimens in the grips of the torsional testing machine, two types of circular steel plates with drilled holes were designed and manufactured. During forming, the bottom plates of 15 mm thickness were anchored in the specimens on their top and bottom through 6 bolts M12/65. Then, top plates of 10 mm thickness were bolted to these plates through 6 bolts M12/20. These plates hold the specimen directly in the grips of the torsion testing machine from the top and bottom through M28/70 bolts. The full device for testing the K_{IIIc} is shown in Fig. 4, whereas a group of devices prepared to fracture toughness tests is shown in Fig. 5.

3.4.3 Testing procedure

The specimens were tested on the axial torsional testing machine MTS 809 Axial/Torsional Test System in accordance with the load diagram shown in Fig. 6. In a similar manner, the fracture toughness test K_{Ic} on cylindrical specimens with spiral initial cracks was carried out Wang *et al.* (2010). During experiments, the angle of rotation (θ) was steered at the zero axial force. A small increase in θ at 0.5°/min was assumed, so that a critical torque (T_Q) is reached after a few minutes after the start of testing. Values T_Q and θ, at which the failure of the specimens occurred, were analysed in the testing.

3.4.4 Fracture toughness K_{IIIc} calculation

The antiplane shear fracture toughness (Mode III) can be estimated by two fracture mechanics parameters: the fracture toughness–K_{IIIc} (Suresh and Tschegg 1987, Reardon and Quesnel 1995, Qin 2005) or the fracture energy–G_{IIIc} (Bazant and Prat 1988, Bazant *et al.* 1990, Ehart *et al.* 1998). In this paper, basing on the experimental results, fracture toughness K_{IIIc} can be concluded, which was determined according to the formula (1) (Miannay 1998).

$$K_{IIIc} = \frac{\tau_{\max} \cdot \sqrt{2\pi r}}{\cos\left(\frac{\theta}{2}\right)}, \tag{1}$$

where, $\tau_{\max}$, maximum stress, MPa; r, radius of twisted surface, m; θ, the angle at which the specimen failed, deg.

Table 3 Compressive strength of concretes

Concrete	Compressive strength (MPa)	s (MPa)	ν (%)
FA-00	47.51–(100% -comparative concrete)	2.55	4.58
FA-20	48.96–(103.1% in relation to FA-00)	3.02	7.53
FA-30	45.10–(94.9% in relation to FA-00)	3.25	7.87

Table 4 Fracture toughness K_{IIIc} of concretes

Concrete	Fracture toughness K_{IIIc} (MN/m$^{3/2}$)	s (MN/m$^{3/2}$)	ν (%)
FA-00	2.49–(100% -comparative concrete)	0.20	8.03
FA-20	2.60–(104.4% in relation to FA-00)	0.24	9.23
FA-30	2.14–(85.9% in relation to FA-00)	0.21	9.81

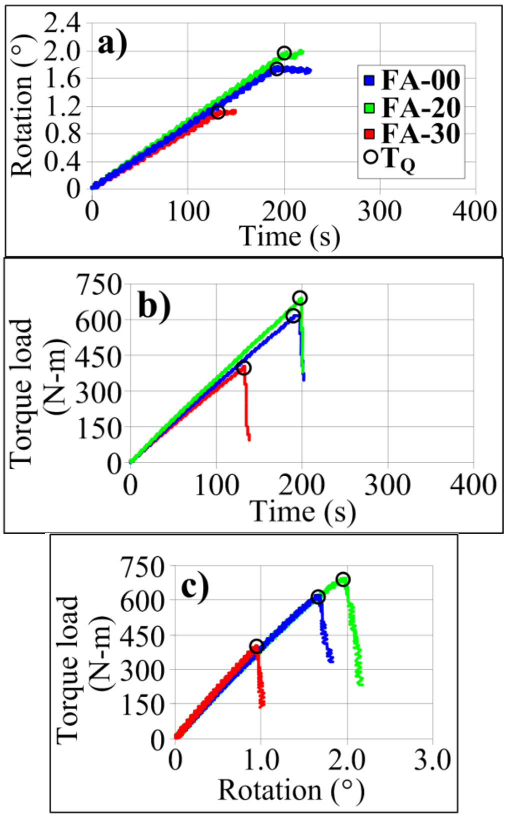

Fig. 7 Examples of graphs obtained from the testing: (a) θ vs t, (b) T vs t, (c) T vs θ

4. Test results and evaluation

4.1 Compressive strength

Table 3 shows the average results of the compressive strength of concretes containing the FA with statistic parameters (standard deviation–s and coefficient of variation–ν). Based on the obtained results, it can be concluded that the 20% additive causes an increase f_{cm} after 28 days of curing by 3.1 percent, while the 30% FA additive causes a drop of this parameter by 5.1 percent.

4.2 Fracture toughness K_{IIIc}

Based on the data recorded during the tests, graphs of:

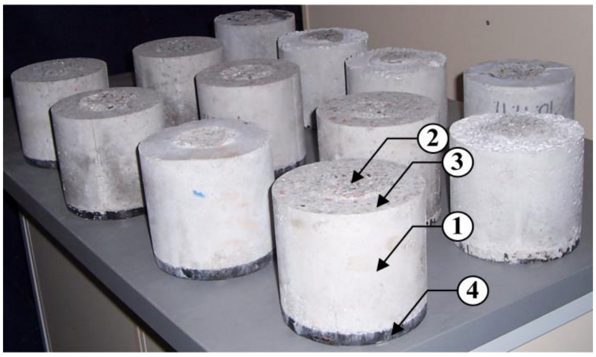

Fig. 8 A view of fractured specimens after the fracture toughness test, showing the failure surfaces; 1-a half of the cylinder, 2-failure surface, 3-the place where the insert was placed, 4-bottom plate

angle of rotation (θ) vs time (t), torque (T) vs t and T vs θ were plotted and values of fracture toughness were calculated. The average values of the fracture toughness after 28 days of curing with statistic parameters s and ν are gathered in Table 4, whereas examples of graphs of the analysed relationships for one of the specimens (for all series of concrete) are shown in Fig. 7.

The failure, i.e., the moment when the specimen no longer carry the torque, is usually characterized by:

- a sudden collapse on the graph T-θ (Fig. 7(c)),
- a constant value θ maintained for at least several seconds (Fig. 7(a)).

All specimens during testing underwent planar failures at the point where initial cracks were filled within a few minutes after the application of the load. Fig. 8 shows a view of tested specimens with characteristic planar fracture surfaces. The same type of fracture is also presented by Bazant *et al.* (1990).

The obtained results lead to conclusion that the 20% FA addition caused increase of K_{IIIc} by 4.4%, while the replacement of a part of cement with a 30% additive of the FA brings about 14.1% reduction of the fracture toughness in comparison to the concrete without the FA. The above results are partially convergent with the results of the compression strength tests (Table 3). The increase of f_{cm} in case of composite FA-20 and the decrease of this parameter in case of the composite with a 30% addition of this filling material were observed. Similar trends in obtained results were observed when testing the same composites at the Mode II fracture (Golewski and Sadowski 2012, Golewski *et al.* 2012, Golewski and Sadowski 2014). The average values of the fracture toughness K_{IIc} with statistic parameters s and ν are gathered in Table 5.

Based on a comparison of the values of the fracture toughness for Mode II and III fracture, it was found that the ratio K_{IIIc}/K_{IIc} for all series of concrete was equal to 0.59. High similarity in the obtained results, can indicate a very accurate and precise testing for analysed modes of cracking.

Moreover, when comparing the results from the testing for Mode II and III fracture, a greater accuracy (smaller coefficients of variation) of results K_{IIIc} in comparison to K_{IIc} was observed. This might have been due to: precise preparation of specimen by preparing the special device for

Table 5 Fracture toughness K_{IIc} of concretes

Concrete	Fracture toughness K_{IIc} (MN/m$^{3/2}$)	s (MN/m$^{3/2}$)	ν (%)
FA-00	4.24–(100% -comparative concrete)	0.65	9.43
FA-20	4.39–(103.5% in relation to FA-00)	0.81	11.63
FA-30	3.65–(86.1% in relation to FA-00)	0.78	12.11

fracture toughness (Fig. 4), and the use of very precise axial torsion machine MTS 809 with recording the results on a computer (Fig. 6).

Modification of the concrete structure with active mineral additives, such as the FA, is justified by ecological as well as economic reasons. The tests showed that this active filing material has beneficial influence on delaying the destructive processes in the material and on the increase of the material's fracture toughness.

The replacement of 20% of cement with the additive of active pozzolana class F FA caused the increase of the K_{IIIc} (Table 4) parameter of the concrete after 28 days of curing. Moreover, it was observed that the concrete from the batch FA-20 had higher compression strength than the concrete without additives (Table 3). Similar positive results of compressive strength of composites with 20% FA additive observed Chindaprasirt and Rukzon (2008)-during testing of mortar and Ratish Kumar *et al.* (2014)-during testing of concrete.

The beneficial effect of 20% siliceous FA addition on the parameters of different composites was also observed in the studies (Sekulic *et al.* 1999, Jing *et al.* 2008, Sabet *et al.* 2013, Nadeem *et al.* 2014). Based on these tests, it was found that the additive of siliceous FA in the amount of 20% is beneficial for:

• increase in the specific surface area of mechanically activated FA (Sekulic *et al.* 1999),
• increase in the tobermorite phase (Jing *et al.* 2008),
• significant increase in electrical sensivity of SCHP concrete (Sabet *et al.* 2013),
• better performance of concrete at temperatures of 400℃ and above (Nadeem *et al.*. 2014).

After 28 days of curing, the composites containing 30% addition of FA were characterized by lower strength parameters (Table 3) as well as reduced fracture toughness K_{IIIc} (Table 4).

5. Conclusions

The following conclusions can be drawn from the present investigation.

• The siliceous FA additivies clearly change the antiplane shear fracture toughness K_{IIIc}.
• 20% FA additive causes a small increase of K_{IIIc} while 30% FA additive causes a significant decrease in fracture toughness.
• Results of fracture toughness obtained at Mode II and Mode III fracture are convergent qualitatively.
• Proportions of stress intensity factors K_{IIc} and K_{IIIc}, which are K_{IIIc}/K_{IIc}=0.59 indicate that the greater fracture toughness-by approximately 70%-have concretes at the Mode II fracture as compared to the Mode III.

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