Effect of Silica Fume and Siliceous Fly Ash Addition on the Fracture Toughness of Plain Concrete in Mode I

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Abstract. Nowadays, structural concretes should meet strict requirements such as: strength, durability, and resistance to adverse weather conditions and corrosion. Therefore, research on modifying concrete with mineral additives and chemical admixtures is conducted. Siliceous fly ash (FA) and silica fume (SF) are by-products of industrial processes and their application to the concrete mixtures can improve both parameters of composites, as well as greatly contributing to environmental protection. This paper presents the results of fracture toughness tests, specified at the Mode I fracture (tension at bending; opening mode), based on RILEM Draft Recommendations. The experiments were carried out after 28 days of curing of plain concrete, which consisting the following additives: 10% SF + 0% FA, 10% SF + 10% FA, 10% SF + 20%FA. To assess mechanics parameters compressive strength tests and fracture toughness tests were conducted. Fracture toughness tests were carried out on MTS 809 Axial/Torsional Test System. In our studies, the fracture toughness of the composites based on the experimental results of critical stress intensity factor $K_{IC}$. Detailed analysis of the obtained results lead to conclusion that the combined addition of FA and SF clearly changes the fracture toughness according to the Mode I fracture.

1. Introduction

The 21st century is a huge challenge for construction engineers. It is marked by the search for new technological solutions and modern construction materials. Are used, among others hybrid innovative techniques based on the synergy of the combined components together. An example of such materials are binary, ternary or even quaternary binders with the use of mineral additives, e.g. [1-4]. These include, among others, fly ash cements with the addition of silica fume [5-8]. Currently, many research centers conduct research both on the separate use of SF [9,10] and FA for concrete, as well as tests assessing the properties of composites, to which a combined addition of both materials was used.

Siliceous fly ash (FA) is a by-product obtained in the process of hard coal combustion performed in electric power stations and in thermal-electric power stations [11-13]. It is removed by mechanical collectors or electrostatic precipitators as a fine particulate residue from the combustion gases before they are discharged to the atmosphere. Furthermore, FA from coal combustion processes is not hazardous from the radiological point of view [14].

Silica fume (SF) is a byproduct of producing silicon metal or ferrosilicon alloys. SF consists primarily of amorphous (non-crystalline) silicon dioxide (SiO$_2$). The individual particles are small, approximately 100 times smaller than the size of the average cement particle. Because of its chemical and physical properties, i.e.: fine particles, large surface area, and the high SiO$_2$ content, SF is a very reactive pozzolan when used in concrete. Moreover it should be added that, modification of the concrete structure with
active mineral additives, such as FA or SF, is justified by ecological as well as economic reasons, e.g. [15]. Damages to concrete in the form of microcracks and cracks are one of the main reasons for deterioration of its physical and mechanical parameters and finally destruction of the material. Therefore, in order to increase the durability of concrete and other materials, it is necessary to know not only the basic strength parameters of these composites, but also the parameters of fracture mechanics, e.g. [8,9,16-29].

2. Experimental details
The paper presents the results of research on the macroscopic assessment of fracture toughness of concrete according to the first model of cracking. Own research allowed to define the basic parameter of fracture mechanics that is the critical stress intensity factor \( K_{IC} \) [30-35]. Additional studies were compressive strength \( f_{cm} \) and the splitting tensile strength \( f_{ct} \).

The mixtures were made with the following composition of additives:
- 0% FA+10% SF (FA-00+SF-10),
- 10% FA+10% SF (FA-10+SF-10),
- 20% FA+10% SF (FA-20+SF-10).

The type of materials used for making the mixtures and the mix proportion of the concretes composition are shown in Table 1. The compositions of concrete mixtures were selected in such a way that one can compare the effect of both pozzolanic additives, used in different amounts, on the analyzed concrete parameters. In all series of concrete, the constant amount of the binder substitute at 10% was SF. A variable parameter was the addition of FA, which replaced the Portland cement in the amount of: 0, 10 and 20%.

Table 1. Details of concrete mixtures (kg/m³)

| Component of the mixture                        | Type of concrete     |
|------------------------------------------------|----------------------|
| Portland cement CEM I 32.5R                    | FA-00+SF-10          |
| Siliceous fly ash                              | 317                  |
| Silica fume - concentrated                     | 0                    |
| Water                                          | 141                  |
| Sand 0–2 mm                                    | 676                  |
| Gravel 2–8 mm                                  | 1205                 |
| Plasticizer – Stucheplast 125                  | 2                    |

For each type of concrete mixture were made:
- 6 cubic samples (150 mm) for compressive strength tests according to PN-EN12390-3,
- 6 cubic samples (150 mm) for splitting tensile strength tests according to PN-EN12390-6,
- 6 beams (80 x 150 x 700 mm) for fracture toughness tests at mode I fracture.

After demoulding the samples cured for 14 days in water and then until the 28th day in laboratory conditions. After 28 days, the strength tests of concrete were made on the Controls Advantest 9 hydraulic press. The obtained average results are presented in Table 2. In this Table also gives the coefficients of variation \( v_{f_{cm}} \) and \( v_{f_{ct}} \) for the tests carried out.

Table 2. Compressive strength and splitting tensile strength results

| Type of concrete | \( f_{cm} \) (MPa) | \( v_{f_{cm}} \) (%) | \( f_{ct} \) (MPa) | \( v_{f_{ct}} \) (%) |
|------------------|--------------------|----------------------|-------------------|----------------------|
| FA-00+SF-10      | 59.40              | 4.38                 | 4.22              | 8.63                 |
| FA-10+SF-10      | 59.50              | 3.73                 | 3.52              | 6.99                 |
| FA-20+SF-10      | 56.33              | 7.34                 | 3.30              | 3.44                 |
3. Mode I fracture test
Fracture toughness tests were carried out on MTS 809 Axial/Torsional Test System. The study was based on the RILEM draft recommendation [36] in a stand similar to that presented in [24,34]. The experiments were performed for the loading scheme presented in Fig. 1. Sample dimensions in detail were also shown in Figure 1.

Figure 1. Schematic drawings of the specimen used in the fracture toughness examination according to mode I: HO – clamp gauge holder thickness, a₀ – height of initial crack, CMOD – crack mouth opening displacement.

To assess the fracture toughness of concrete, in the Mode I fracture, we used beams with the dimensions 700 x 150 x 80 mm which had one initial centrally crack. The beams were subjected to 3-point bending test. They were made in demountable bolted wooden forms (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. A special experimental stand was prepared as shown in Fig. 4. All necessary results, needed to determine the critical stress intensity factors for concretes, were obtained with application MTS 809 testing machine. 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.

Figure 2. A sample for testing after formation

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 zero, the
test specimen was loaded again. After that the cycles were repeated until the beams were broken into 2 parts (Fig. 4). The whole cyclic deformation processes were described by the following curves: Force ($F$) – crack mouth opening displacement (CMOD) (Fig. 3) and $F$ – deflection ($f$).

The obtained results allowed for determination of the fracture toughness $K_{IC}$ using the formula given in RILEM recommendations [36].

![Figure 3. An exemplary failure curve for FA10 + SF10 series concrete (Force-CMOD): $C_i$ – initial compliance, $C_u$ – unloading compliance.](image)

### Table 3. Results of fracture toughness tests.

| Type of concrete | $K_{IC}^*\ (\text{MN/m}^{3/2})$ | $\nu\ (%)$ |
|------------------|-------------------------------|------------|
| FA00+SF10        | 1.34                          | 6.99       |
| FA10+SF10        | 1.40                          | 15.23      |
| FA20+SF10        | 1.33                          | 5.57       |

Based on the results obtained from the study, it can be observed that after 28 days the highest values were obtained using a combined addition of 10% SF and 10% FA. Based on the analysis of the results obtained in own research (Table 3), it can be concluded that the addition of FA to concrete caused an increase in the basic parameter of fracture mechanics - $K_{IC}^*$. In the case of FA00+SF10 and FA20+SF10 by 5.0%.

The use of 10% FA to the mixture did not reduce the compressive strength. Slightly compressive strength decreased with 20% FA.
Figure 4. The sample placed in MTS 809. a) before the test, b) the sample after the test.

4. Conclusions
From this research the following conclusions can be formulated:
1. The FA and SF additives change the fracture toughness $K_{IC}$ in relation to the ash concretes.
2. The concretes with the FA and SF has a higher from 20% to 30% are fracture toughness compared to reference concrete and concrete with the addition of only FA.
3. The addition of SF to ash concrete results in a significant increase in their compressive and tensile strength.
4. The most favorable compressive strength and fracture toughness results are obtained by replacing 20% of the cement mass in the concrete mix with the total addition of FA and SF in the same amount.

5. References
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