An Analysis of Fracture Toughness in Concrete with Fly Ash Addition, Considering all Models of Cracking

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Abstract. This paper presents results of tests of fracture toughness of concrete modified with the addition of class F fly ash (FA), covering all three models of cracking: I, II, and III. Knowing the values of critical stress intensity factors: $K_{IC}$, $K_{IIc}$ and $K_{IIIc}$, generalized fracture toughness $K_c$ was determined. The tests were carried out on concrete composites with a different content of FA, i.e.: 0% (FA-00), 20% (FA-20) and 30% (FA-30). The tests were performed out after 28 days, i.e. the standard period of curing of the specimens. Based on the obtained results it can concluded that the class F FA additive in the amount up to 30% of mass of cement clearly changes the fracture toughness of concrete, at all models of cracking. Concrete with a 20% addition of FA – FA-20 is characterized by the most favorable mechanical parameters, whereas composite with a 30% addition of FA – FA-30 had low compressive strength and generalized fracture toughness. Moreover, the results of fracture toughness tests, are convergent qualitatively with compressive strength results.

1. Introduction

Concrete is currently the most often used and most important material in modern construction. It serves not only the role of material allowing the construction of: residential buildings, offices, public buildings and production halls, but also fulfils many other important functions in the social life of man – like for example protection of people from the effects of environmental pollution through the use of concrete structures such as: sewage disposal systems and sewage treatment plants, desulfurization installations and evacuation of combustion gases in heat plants, power plants and combined heat and power plants, acoustic screens for motorways and expressways, protection from radioactive sources in hospitals and nuclear power plants.

Due to the versatile possibilities of use, concrete composites are produced in such high quantities that it is difficult to imagine the functioning of modern civilisation without their presence in the construction industry. However, despite the fact that this materials has been widely used for decades, it has undergone frequent modifications and improvements over this time. In addition, it should be kept in mind that modern concrete, in most cases, is no longer a three-component mineral composite made of cement, aggregates and water, but is also composed of mineral additives and chemical admixtures, e.g. [1–7].

The concrete composites with mineral additives have gained more economic importance in recent years mainly due to the significant development of sustainable construction. It should be noted that 3 main postulates of sustainable construction state that:
• renewable raw materials should not be consumed faster than they can be regenerated,
• non-renewable raw materials should not be consumed faster than they can be replaced by renewable substitutes,
• pollution and waste should not be generated faster than nature can absorb them, recycle or dispose.

Unfortunately, the production of the basic binder for the production of concrete, i.e. Portland cement CEM I, contradicts the above postulates. First of all, the cement industry is one of the largest emitters of greenhouse gases (GHG), due to the fact that his branch of economy generates around 7% of total CO₂ emissions worldwide, e.g. [8]. The technological process in the cement industry, which generates the most CO₂, is the production of cement clinker in rotary kilns. Therefore, the production of pure CEM I Portland cement, containing the largest amount of clinker, causes the highest CO₂ emission. Increasing the share of mineral additives in the composition of cement and reducing the share of clinker is therefore a solution for the reduction of CO₂ emission by the cement industry.

On the other hand, the reduction of cement binder in the composition of the concrete mix has a positive effect on the reduction of CO₂ emission and also the reduction of the level of energy generated in the Portland cement production process.

Moreover, it is known that the Portland cement production process requires the consumption of not only large amounts of energy, but also a significant amount of raw materials. Therefore, an additional benefit of the presented treatments, i.e. substitution of cement with mineral additives, is the protection of natural resources such as: clay, marl, chalk and limestone – which are used to produce Portland clinker.

Taking into consideration the above reasons, it should be stated that the replacement of cement with mineral additives is an important task from the ecological point of view and is clearly environmentally friendly activity [9–11].

Detailed classification of various materials used as substitutes for cement binder in the concrete structure is given in [12]. According to information contained therein, the most commonly used raw material from the group of mineral additives being industrial wastes is fly ash (FA).

Coal Fly ash has no elevated rates indicating its radioactivity [13] and moreover the presence of this additive affects both the concrete mix and the properties of hardened concrete. Spherical, glassy grains of FA (Fig. 1), e.g. [10, 14] cause the effect of "ball bearing", improving the workability of the mix and reducing its water demand by 5-15%. The effect of FA on the microstructure of concrete is both physical and chemical [15–17]. FA exhibit high pozzolanic activity, which leads to the formation of more C-S-H gel. This contributes to the reinforcement of the concrete microstructure both in the area of the cement matrix and in the contact zone between the aggregate and the paste. As the FA grains are smaller than cement grains, their presence in the paste improves the tightness of the cement matrix and thus the durability of the concrete. On the basis of the studies presented in [12, 18], it was shown that mature concrete with 20% FA additive had significantly smaller crack widths in the Interfacial Transition Zone (ITZ) between coarse aggregate and cement matrix than plain concrete.

![Figure 1: Spherical glassy grains of fly ash.](image-url)
The most common and most frequently used method of assessing the quality of concrete composites is the compressive strength test. However, this method is insufficient in the light of the research concerning the mechanism of concrete destruction. Based on this research, it is found that the concrete strength is closely connected with a phenomenon of initial cracks development. It should be added that microcracks always appear in the structure of concrete composites, and they are the result of complex processes associated with concrete curing. The inevitable defects and inhomogeneities occurring in the composite structure cause the concentration of stresses. As a consequence of these phenomena – in the place of the highest concentration of stresses – the development of microcracks begins, initially they are straight cracks and subsequently they are wing ones. During subsequent stages of material destruction, the microcracks combine into chains creating a system of spatial fractures, which consequentially leads to loosening the material structure and destruction of the structural element [19–23].

Therefore, compressive strength does not sufficiently characterize the concrete composite, the destruction of which occurs not as a result of exceeding average stresses measured during the compression strength test, but as a result of achieving sufficient energy in a place of the highest concentration of stresses (in the area of the longest, the widest or the sharpest microcrack).

Observations of the destruction process of concrete specimens during compression tests prove that frequently, an increase in force occurs even when the specimen has already cracked, that is when it has already been failed. The inadequacy of the compressive strength tests is eliminated in respect of fracture toughness tests. In these experiments, the value of critical force and critical stresses are determined at the time of rapid propagation of the initial crack.

Therefore, this paper presents results of tests of fracture toughness of concrete modified with the addition of FA, covering all three models of cracking: I, II, and III. Knowing the values of critical stress intensity factors \( K_{Ic} \), \( K_{IIc} \) and \( K_{IIIc} \), e.g. [24–27] generalized fracture toughness \( K_c \) was determined based on Equation (1) [28].

\[
K_c^2 = K_{Ic}^2 + K_{IIc}^2 + \frac{K_{IIIc}^2}{1 - \nu}
\]

(1)

where: \( \nu \), is Poisson’s ratio.

Since, in the literature there are no results of tests of fracture toughness in concrete containing FA, including all models of cracking, in this paper presents a comprehensive analysis of this problem. The tests were carried out on concrete composites with a different content of FA, i.e.: 0% (FA-00), 20% (FA-20) and 30% (FA-30). The tests were performed out after 28 days, i.e. the standard period of curing of the specimens.

2. Materials and methodology

2.1. Materials

The concrete mixtures were prepared from: Ordinary Portland Cement (OPC) CEM I 32.5 R, a pit sand with a maximum size of 2.0 mm (as fine aggregate), natural gravel with a minimum and maximum size of 2.0 and 8.0 mm (as coarse aggregate), class F fly ash (Blaine fineness – 0.364 m\(^2\)/g, specific gravity – 2.14 g/cm\(^3\)), plasticizer (Basf Liquol BV-18) and the laboratory pipeline water.

2.2. Mixture design and specimens used in the studies

The methodology used for determining the composition of the mixtures relies on replacing a suitable amount of the cement volume (the 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. The concrete mixture proportions are summarized in Table 1. All mixtures had the same water-binder ratio \( w/b = 0.4 \).
Table 1. Summary of concrete mixture proportions (kg/m³)

| Mixture | OPC | FA | %FA | Sand | Gravel | Water | Plasticizer |
|---------|-----|----|-----|------|--------|-------|-------------|
| FA-00   | 352 | 0  | 0   | 676  | 1205   | 141   | 2           |
| FA-20   | 282 | 70 | 20  |      |        |       |             |
| FA-30   | 246 | 106| 30  |      |        |       |             |

The scope of the studies included the performance of the following tests:

- compressive strength – $f_{cm}$, on cubic specimens (150 mm),
- fracture toughness under mode I fracture – $K_{lc}^S$, on beams (80 × 150 × 700 mm) with one initial crack (Fig. 2a),
- fracture toughness under mode II fracture – $K_{IIc}$, on cubic specimens (150 mm) with two initial cracks (Fig. 2b),
- fracture toughness under mode III fracture – $K_{IIIc}$, on cylindrical specimens with a diameter of 150 mm and a height of 300 mm having an initial circumferential notch (Fig. 2c).

It should be added that all tests for all types of composites were carried out on 6 specimens after 28 days of their curing.

Figure 2. Specimens used in studies of the fracture toughness under mode: a) I, b) II, c) III, F-force, T-torsional moment; dimensions in mm.

2.3. Compressive strength tests and fracture toughness examination

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 (described in section 2.2) according to the standards of series EN 12390.

Dimensions of all specimen for fracture toughness tests with loading conditions was shown in Fig 2, whereas views and descriptions of the experimental stands are presented in details in the following papers:

- [20] – for the first model of cracking,
- [16] – for the second model of cracking,
- [17,22] – for the mode III loading.

The testing of Mode I fracture toughness $K_{lc}^S$ was performed according with the draft guidelines of RILEM recommendations [29]. A detailed description of the fracture toughness test for the first model of cracking are given in [9,10,20].

Fracture toughness $K_{lc}$ was determined according to the equation proposed by Watkins [30]. The methodology for determining this factor was given in [16,20].
In order to determine the fracture toughness $K_{IIIc}$, a special innovative device was designed and manufactured [8,15, 17,22,23]. This device has also been patented. A detailed description of the fracture toughness test for the third model of cracking (anti-plane shear) are given in [8,15,17,22,23]. Fracture toughness $K_{IIIc}$ can be calculated, according to the equation proposed by Miannay [31].

With the known values of fracture mechanics parameters for all models of cracking, it was possible to designate a generalized fracture toughness of the material – $K_c$ from the Equation (1).

3. Results and discussion
Table 2 presents the average values of compressive strength $f_{cm}$ and fracture toughness for all models of cracking, i.e.: $K^S_c$, $K_{IIc}$ and $K_{IIIc}$. The table also includes standard deviations $\delta$ from all experiments. The last column of Table 2 gives the results of the calculated generalized fracture toughness $K_c$.

| Concrete | $f_{cm} \pm \delta$ | $K^S_c \pm \delta$ | $K_{IIc} \pm \delta$ | $K_{IIIc} \pm \delta$ | $K_c$ |
|----------|---------------------|---------------------|----------------------|----------------------|-------|
| FA-00    | 47.51 ± 2.55        | 1.06 ± 0.10         | 4.24 ± 0.40          | 2.49 ± 0.20          | 5.03  |
| FA-20    | 48.96 ± 3.02        | 1.09 ± 0.11         | 4.39 ± 0.51          | 2.60 ± 0.24          | 5.22  |
| FA-30    | 45.10 ± 3.55        | 0.93 ± 0.10         | 3.65 ± 0.42          | 2.14 ± 0.21          | 4.33  |

A precise analysis of the test results given in Table 2 leads to the conclusion that, after 28 days of curing, the 20% FA addition causes the increase of the analyzed mechanical parameters $f_{cm}$ and $K_c$ by 2% to 3%. Unfortunately, composites with a larger amount of additive are characterized by lower values of compressive strength and generalized fracture toughness by more than 5%.

Based on the results of the above tests, it can be concluded that the addition of FA in the amount of 20% has a very positive effect on the structure of concrete composites, causing an increase in fracture toughness of the material. However, increasing the amount of the additive by 10% has a significant negative effect on the values of mechanical parameters in such concrete (Table 2).

Additionally, when analyzing Table 2, it was also found that compressive strength values $f_{cm}$ are qualitatively convergent with generalized fracture toughness $K_c$ of concrete with the addition of FA (Table 2).

4. Conclusions
The following conclusions can be drawn from the present investigation.
1. The class F fly ash additive in the amount up to 30% of mass of cement clearly changes the fracture toughness of concrete, at all models of cracking, after 28 days of curing.
2. Concrete with a 20% addition of FA is characterized by the most favorable mechanical parameters.
3. The results of fracture toughness tests, are convergent qualitatively with compressive strength results.

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