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Improvement of fracture toughness of green concrete as a result of addition of coal fly ash. Characterization of fly ash microstructure

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ABSTRACT

Composites with the addition of coal fly ash (CFA) can be included in the sustainable and green concrete. Effective promotion of green concrete incorporating CFA is necessary to minimize the threat to the environment posed by CFA waste disposal and to reduce cement consumption thus cutting CO_2 emissions.

This study investigates the influence of the curing time on the fracture toughness of concrete produced with different concentrations of CFA. Concentrations of 20% – CFA-20 and 30% – CFA-30 of CFA were used and the results were compared with a reference mixture with 100% Ordinary Portland Cement (OPC) – CFA-00. Compressive strength – f_{cm} and fracture toughness under mode I – K_{Ic}^S (tension at bending), were determined after: 3, 7, 28, 90, 180 and 365 days.

The results obtained lead to the conclusion that, it is possible to make green concrete containing CFA with high fracture toughness. Furthermore, this is one of the ways to reduce cement industry CO_2 emissions.

20% additive of CFA guarantees high fracture toughness in mature concretes, whereas concrete with 30% CFA additive is characterized by highest dynamic increase of the parameter K_{Ic}^S.

The experimental program was completed by the analysis of microstructure of CFA by using SEM. These studies showed that the main morphological forms in the CFA are single grains, such as: pyrospheres, cenospheres, plerospheres, multispheres, ferrospheres, grains of irregular shapes, and amorphous grains. Grains of CFA may also occur in larger quantities, as: jointed grains, clusters and agglomerates.

1. Introduction

Nowadays, the design of concrete compositions sticks to the principles of the sustained development and ecology. 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 – not only have a beneficial effect on the reduction of CO_2 emission but also constitute the basis of the so-called sustainable – green concrete concept [1–3].

The 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 minimum. In this context, responsible green construction should be energy efficient and made of environmentally friendly materials. Furthermore, green buildings are necessary component of securing sustainability. Interesting suggestions for designing more sustainable and greener concrete were presented in [4].

It should be noted that for over several dozen years, with the development of a new generation of concrete composites, the production of concrete mixtures containing different classes and types of supplementary cementitious materials (SCMs) [5], often having pozzolanic properties [6] has significantly increased. Among them there are: silica fume [7], ground granulated blast furnace slag [8], and fly ashes class F [9,10] and class C [11].

Cement substitution is important for sustainable construction because the 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 [12].

For these reasons, the utilization of SCMs has been found as a suitable alternative to reduce CO_2 emissions from cement production. On the other hand, CFA is the most well-known of these materials and has been used for decades in cement applications. Among them, 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.

As CFA is a by-product obtained in the process of hard coal combustion, there are hundred millions tons of industrial waste produced annually across the World. Up to day – 750 million tons of the CFA is generated each year in the World [13] and in future one should expect this quantity to increase to 2100 million tons in 2031–32 [14].

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Nowadays, there is much research into the ability of CFA to enhance: construction, mining, and terrain management. The analyses of use of CFA in the construction industry reveal that more than 50% of this material is used in the cement industry as a cement replacement material. Therefore, in my studies, I focus on concrete composites modified with different CFA additives.

The properties of concrete materials, including their durability, mainly depend on the structural factors and the interaction between micro- and macrostructure of the material. Cracks and losses are two basic defects of the concrete structure. They may reduce the load-bearing capacity, leak tight integrity, and stiffness of elements and structures, which, in extreme cases, may lead to failures and even building catastrophes. According to [10] cracking is one of the primary causes of deterioration in concrete composites and concrete structures.

Therefore, the engineers designing concrete mixtures should be familiar with the processes of crack initiation and of propagation of structural materials, especially those that are characterized by high brittleness. Such knowledge would allow them to enhance the quality of concrete destinied for structures, to estimate defects and determine their causes, and, finally, to obtain composites with the highest levels of durability and reliability.

The overall objective of the conducted scientific analyses was a description of fracture processes in concretes with the CFA 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 the effect of the CFA additive on the basic physical and mechanical characteristics of concrete could be thoroughly explored. However, closer look at the literature devoted to this area of science suffices to reveal a scarcity of complete data related to the analysis of initiation and propagation of microcracks and cracks developing in result of the impact of complex stress states on concrete.

Coal fly ash is a pozzolanic material that demonstrates binding capacity through active CFA ingredients (mainly SiO_2 and Al_2O_3) calcium hydroxide. These reactions lead to the increase of C-A-S-H and C-S-H phase in concrete, which has a significant effect on the properties of concrete, e.g. [15–17]. The introduction of CFA to the composition of cement causes changes in the phase composition and the microstructure of cement paste, which is important for 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 increasing external loads, development, accumulation and, consequently the premature material destruction occurs.

The reduction of strength of concrete results from the initial structural defects existing inside material [18]. 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 [19].

Failure of concretes is a multi-stage process that is conditioned by level and type of the applied external loads as well as by the internal structure of composite [20]. Therefore, in the case of concrete and many other materials fracture toughness is an important material parameter [21–25]. On the other hand, cracks initiation and propagation in 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 of concrete at all scales, whereas cracks are initiated and grow in the mixed mode loading. 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 provided for three separate fracture modes, i.e.:

- 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 containing CFA the available results of experiments concern mainly the first mode fracture and, more rarely, the second one. Fracture toughness under mode I – K_{Ic} and mode II – K_{IIc} for plain concretes containing the CFA additives are the topics of several articles [26–30], while only three papers present the fracture toughness for the mode III – K_{IIIc} [31–33] and W_f [20]. An additional problem is the fact that all previous papers usually refer to the study of the fracture toughness of concrete containing significantly different amount of CFA (from 20 to 55%) usually after 28 (and, optionally, after 56) days of their curing.

In this paper, the reason to initiate the work on fracture processes analysis in concretes with the CFA additive lies in the fact that the strength of such materials increase in the process of curing [34]. Due to the slow course of the pozzolanic reaction, which influences directly the mechanical properties of composites of this type, the strength increases slowly at the initial stage of hardening [35]. However, curing over longer time cement with CFA achieves values exceeding the compressive strength of Portland cement of the same strength class.

The present study intends to analyse the concrete at early age and in a period exceeding 28 days changes in compressive strength – f_{cm} and the changes in fracture toughness of concretes [36]. Fracture toughness tests were performed using basic Mode I, e.g. [37], according to the RILEM Draft Recommendations [38].

The tests determined:

- the critical values of stress intensity factors – $K_{Ic}{}^{S}$,
- the effect the age of concretes modified with the CFA has on analysed mechanical properties.

In addition, this paper presents insightful description of CFA macrostructure and microstructure – by using Scanning Electron microscope (SEM) [39].

2. Materials and Research Methodology

2.1. Materials

All experiments were planned for two compositions of concrete mixture, with varying percentage of CFA additive, which is often used in the cement industry. All tests were conducted for green concretes modified with the CFA additive in the amount of 20% (CFA-20) and 30% (CFA-30) of weight of cement. The results of experiments were compared to the values obtained for the reference concrete (CFA-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 [36].

In this investigation, both OPC and CFA were used to form the binder of the concrete. The chemical and physical properties of OPC and CFA are shown in Tables 1 and 2.

Natural gravel of grain size between 2.0 and 8.0 mm was used as a coarse aggregate. Pit sand of size 0–2 mm was used as a fine aggregate.

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.

2.2. Macro- and Microscopic Characteristics of CFA

Coal fly ash, is a by-product obtained in the process of hard coal combustion in electric and thermal-electric power stations. It is formed during a multi-stage pyrolysis of hard coal, thoroughly described in