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Fracture toughness and fracture surfaces morphology of metakaolinite-modified concrete

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HIGHLIGHTS

- Fracture toughness of concrete with metakaolinite additive was studied.
- Metakaolinite increases fracture toughness of concrete.
- Developed model gives possibility for fracture toughness prediction.
- Fractal analysis of concretes with metakaolinite additive is highlighted.
- Fracture toughness correlates with fractal dimension and water/binder ratio.

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ABSTRACT

The authors' main aim was an in-depth study of the issue of fracture toughness of metakaolinite modified concretes, the problem not investigated to a great extent so far. The results of tests on the fracture toughness of metakaolinite modified concretes have proved that it is higher compared with that of non-modified concretes. Fracture toughness increases with the higher addition of metakaolinite. The possibility of relating the morphology of fracture surfaces forming during cracking of concretes modified with the addition of metakaolinite to the fracture toughness, as expressed by the critical stress intensity factor K_{Ic}^{S}, is explored in the paper using statistical apparatus. The mechanical properties and fractal dimension examinations were carried out according to the central composition plan, while assuming two variables: the metakaolinite addition fraction of the binder mass, varying in the range from 2 to 15%, and the water/binder ratio, varying in the range from 0.35 to 0.53. The fractal dimension D_c was calculated by the chord method for profile lines isolated from the fracture surfaces, and then the fractal dimension was related to the fracture toughness as expressed by the critical stress intensity factor, K_{Ic}^{S}.

1. Introduction

The need for advancement of construction materials engineering, materials with cement matrix in particular, generates not only the necessity of the introduction of new modifiers of concrete composition. What is of primary need, however, is to identify the effects of such modification, its impact on the structure, properties and durability of concrete.

One of the promising concrete composition modifiers is calcined kaolinite called metakaolinite (MK). Nowadays, when an alternative for energy consuming cement production, with high CO_2 emission, is searched for and since it is also necessary to find materials that could replace the traditionally used silica fume, the significance of this type of research is indisputable. The number of publications on the effect of metakaolinite on the structure, properties and durability of concrete is increasing [1–17]. However, there is no extensive research on fracture toughness of concrete with metakaolinite additive. The outcomes of the analyses significantly extend the knowledge of the effect of metakaolinite on the fracture toughness of concrete.

Fractal geometry is a science concerned with the description of complex structures in a quantitative manner [18]. This enables the previously limited concept of fractal to be extended. The intervals between the typological dimensions 0; 1; 2; 3 are filled by the fractal dimension. The quantitative measurement of fractals is impossible, as the way of their formation consists in repeating specific activities, that is counting the successive elements of some sequences, ad infinitum. It is possible, though, to determine the roughness of the fractal, which is defined by the fractal dimension. A line is a one-dimension figure, a plane is a two-dimensional one, while a solid is a three-dimensional object. In fractal geometry, a

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dimension does not have to be a natural number. A certain specific figure may be more corrugated than a smooth one-dimensional curve, but, at the same time, more poorly fill up a given surface than a two-dimensional plane does. So, the fractal dimension of such a figure will be contained between 1 and 2. This reasoning can also be extended to cover the surface analysis.

One of the reasons for the interest in fractal geometry of researchers dealing with the study of cement materials is the wish for explaining and describing the phenomenon of their fracturing. Since 1985, fractal geometry has found its applications in the examination of cement paste [19] and then also concretes [20–33]. Winslow [19], who used employed X-ray technique in his research, noticed that the surface of hydrated cement paste was a fractal and that the fractal dimension decreased as the water-cement (w/c) ratio increased. Saouma et al. [20] also demonstrated a multi-fractal nature of concrete fractures. They reported that the fractal dimension on a microscopic scale was $D = 1.2$, while on a macroscopic scale, $D = 1.1$.

Since the inception of the fractal analysis, a relationship between the fracture surface as described by the fractal dimension and the fracture mechanics parameters have been sought for. The first analyses were carried out by Saouma and Barton [20]. They found that the increase in the fractal dimension correlated with the decrease in fracture energy G_F and the critical stress intensity factor K_{Ic}, and the obtained relationships were linear. A linear relationship between the fractal dimension and the fracture energy of concretes with a varying water/binder ratio was also obtained by Yan et al. [21] and Issa et al. [22]. Similar relationship, though obtained for the critical stress intensity factor K_{Ic} were also obtained by Prokopski and Langier [23]. When examining concretes made based on three types of aggregate, namely a basalt, gravel and dolomite ones, after 7, 14, 28 and 90 days of curing, Prokopski and Konkol [24] showed the existence of linear relationships for the dependence of the critical stress intensity factor K_{Ic}, of the elastic modulus E, and the compressive strength, f_c, on the fractal dimension, D_c, as determined by the chord method. The increase in the fractal dimension correlated with the increase in all of the examined parameters. It was also observed that with increasing concrete age, the values of all of the mechanical parameters tested (K^S_{Ic}, f_c and E) increased, with a similar fractal dimension value (irrespective of the concrete age) within the same concrete, which might suggest a fracture being "programmed" in the structure. It was found, at the same time, that high-strength concretes exhibited a smaller values of the fractal dimension D compared to ordinary concretes, which was explained by the lesser complexity of the fracture surface of high-value concretes compared to the fracture surface of ordinary concretes. The proposition was put forward that the fraction surfaces of a concrete characterized by higher strength were more flat as a result of the cracking taking place across the coarse aggregate grains (intergranular crack propagation).

The relationship between the fracture mechanics parameters and the fractal dimension was the subject of study [27]. Theoretical discussion for an infinite plate subjected to loading with a fractal-type fracture was compared with experimental tests on three-point bend concrete beams with a primary crack. A constitutive concrete failure model in the Euclidean space was given and generalized to include fractal cases following the variable injury transformation rule.

Fractal geometry is also used for modelling of phenomena in concrete, for example the behaviour of microcracks caused by the corrosive action of direct current in reinforced concrete [26]. The action of direct current occurring in reinforced-concrete urban structures contributes to the corrosion of the reinforcement and the steel, which can lead to a failure of the structure. Study [26] used a fractal model for simulating the growth of internal cracks in concrete, providing also a relationship between the fractal dimension and the fracture mechanics parameters. Modelling of the fracture phenomenon applies also to fatigue fractures [30].

Currently, the obtained relationships between the fracture toughness and the fractal dimension of the fracture surface are utilized in the examinations of concretes using modern laser profilometers [25].

The issue of seeking for a concrete fracture model that will reflect the actual behaviour of the fracture phenomenon still remains topical [28,29]. The model proposed in study [28] represents the approach of relating the macro-properties of a material to the change in its microstructure. In order to verify the model, the obtained solution was compared with the experimental data. The analyses discussed in paper [29] concern fracture Mode I and an unlimited plate subjected to loading with a crack of a length $2a$, while considering fractal fracture effects. To obtain the solution, the modified Griffith criterion was used. The analysis of the concreted fracture parameters was made, depending on the initial fractal crack length and the fractal dimension. The authors of the above-mentioned paper found that the values of the examined fracture parameters (including the stress intensity factor and fracture energy) decreased as the initial crack length increased. This means that the fracture will be more likely to occur in a material with a larger crack.

The analyses described in the present paper are aimed at creating the statistical model of the fracture phenomenon using fractal theory.

2. Experimental details

2.1. Materials and testing plan

For making test specimens, CEM I 32.5R Portland cement, basalt coarse aggregate and a metakaolinite addition were used (Table 1). In the case of metakaolinite, a diversification of particle sizes from 0.1 to 100 μm was obtained, with a majority of particle sizes from 1 to 10 μm (about 60% share). The percentage of grains smaller than 1 μm is about 20%, and grains smaller than 17 μm amounted to 90% (Fig. 1).

Metakaolinite is a product obtained in the controlled process of kaolin calcination at a temperature in the range from 500 to 800 °C. It is a highly reactive mineral with pozzolana properties, containing active forms of aluminium and silicon oxides, which very readily enter into chemical reaction with calcium hydroxide, $Ca(OH)_2$, released during the reaction of the two basic minerals of cement, alite and belite. As a result of the occurring reactions of metakaolinite with calcium hydroxide, products form, which are similar to the Portland cement hydration products in terms of composition and structure [1]. The products of these reactions have a favourable effect on the concrete microstructure causing its sealing by reducing the total and capillary porosities [2,3]. This results in an increase in the tightness of the concrete and an enhancement in its mechanical properties. As has been shown by current publications, metakaolinite is an additive competitive to silica dust that is commonly used for tests [4–8,3,9–17].

Metakaolinite (MK) was used on the binder side by taking out the appropriate mass of cement and substituting it with metakaolinite. The metakaolinite fraction was from 2 to 15% of the total binder mass. 9 concrete mix recipes varying in composition were prepared. The composition of the mixes was determined by the following adopted independent variables: the variable metakaolinite fraction and the water/binder (w/b) ratio. The tests were programmed according to the central experimental plan (Fig. 2) by assuming the range of variability of the second variable, i.e. the water/binder ratio, from 0.35 to 0.53.

For all concrete mixes, the fixed consistence was maintained by batching experimentally the appropriate amount of the FM-6 superplasticizer. A target flow of 42 cm was assumed in the flow table test method. A flow scatter of ±2 cm was obtained. The composition of individual series of metakaolinite-modified concrete mixes is summarized in Table 2.

Control mixes of a varying water-cement ratio without the kaolinite addition were also prepared. The composition of the CC_03 and CC_05 control mixes is also given in Table 2.

2.2. Testing procedure

Mechanical tests were carried out after 28 and 180 days of curing the specimens under humid air conditions at an air relative humidity of >95%.