Determination of fracture parameters of fiber-reinforced cementitious composites containing nano-silica using image processing

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ABSTRACT

Considering that fiber-reinforced cementitious composites have been developed in recent years, it seems necessary to determine their fracture behavior, fix the possible defects of these materials, and facilitate their use in the construction industry. In this study, a new cementitious composite with strain-hardening behavior has been developed. Granulated blast furnace slag has been used as supplementary cement material to reduce the side effects of excessive consumption of cement on the environment. Moreover, Nano silica has been used to increase hydration at early ages due to the low rate of hydration of pozzolanic materials, which leads to low strength at an early age. Therefore, in this study, the effect of adding nano-silica on the fracture behavior of cementitious composites has been discovered. The double-k fracture method (DKFM) has been used to analyze the fracture behavior at different stages of specimen failure, i.e., crack initiation and stable and unstable crack propagation. In addition, the digital image correlation technique has been used to find the initial crack load and the crack opening displacement at different loading stages. This study's results revealed that adding nano-silica to the amount of 3 wt. % of cement improves the mechanical behavior (including compressive strength and bending strength), increases the cohesive toughness, and reduces the brittleness of the fiber-reinforced cementitious composite. Increasing cohesive toughness could be interpreted as an increase in embedded fibers' interfacial frictional bond strength.

KEYWORDS

Fiber-Reinforced Cementitious Composites, Fracture Mechanics, Nano-silica, Image Processing, Digital Image Correlation (DIC)

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1. Introduction

In recent decades, with the expansion of the research done in the construction industry, new construction materials have been introduced as High-performance fiber-reinforced cementitious composites (HPFRCC). Unlike conventional concrete, these special categories of fiber cementitious composites exhibit strain-hardening behavior with multiple cracking prior to ultimate failure leading to a ductile behavior [1, 2]. One of the most important features compared to conventional fiber-reinforced concrete (FRC) is its potential to limit crack width. The width of the cracks is limited to less than 100 μm, which prevents the penetration of the aggressive agent into the composite and makes the composite durable [3].

The fact that cementitious composites contain a large amount of cement, which can be harmful to the environment, is one of the challenges of their widespread use. Mineral additives, such as fly ash and blast furnace slag, have been used to replace part of the cement weight due to their advantages and positive effects on concrete and cementitious products. In recent years, using these materials in cementitious composites has also attracted the attention of researchers [4]. Replacing a part of cement with fly ash and blast furnace slag will reduce cement consumption and will have positive effects on environmental protection because cement production is associated with carbon dioxide production. Despite its positive effects, the use of blast furnace slag powder with pozzolanic reaction causes a delay in setting and low compressive and bending strength at a young age [5].

In order to solve the concretes setting delay problem and fiber composites containing high amounts of natural and artificial pozzolans, lots of research have been carried out in recent years and the effect of adding some mineral nano-materials to mortar containing high amounts of pozzolans has been investigated in order to solve this problem [6].

Nano silica is considered one of the most conventional nano-materials used in concrete due to its positive effect on the microstructure of cement paste. Due to its significant pozzolanic effect, nano-silica particles can consume calcium hydroxide and convert it into CSH gel, facilitate the hydration of cement at an early age, and improve the mechanical properties of concrete. Moreover, by adding nano-silica, the cement paste porosity will decrease due to nano-silica particles' improved performance in the filling effect and particle size distribution [7]. The mentioned features lead to the advantages such as increasing the compressive, bending, and tensile strength of concrete, increasing the resistance of concrete against erosion, significantly reducing the permeability of concrete, and preventing the penetration of chlorine ions, Sulfates, and other destructive chemicals to the concrete.

2. Methodology

2.1. double-k method

In this research, the double-k fracture model provided by Xu and Reinhardt was used to evaluate the fracture properties of Cementitious composite. They considered three stages for crack initiation and growth in concrete, which include crack initiation and stable and unstable crack propagation [8].

By examining the experimental results, they proposed two parameters independent of the dimensions and shape of the specimen. The parameters are: k_{IC}^{ini} : Initiation toughness indicating the inherent ability of the material to prevent cracking under loading; k_{IC}^{UN} : Unstable fracture toughness indicating the total strength of the material in critical conditions. The two parameters are related to each other according to the following equation:

$$\mathrm{K}_{\mathrm{IC}}^{\mathrm{un}} = \mathrm{K}_{\mathrm{IC}}^{\mathrm{ini}} + \mathrm{K}_{\mathrm{IC}}^{\mathrm{C}} \quad (1)$$

In the above equation, k_{IC}^{C} is the critical stress intensity factor due to cohesive stresses. The brittleness number, a dimensionless parameter, is defined as follows. The brittleness parameter is a number between zero and one [9].

$$\beta_B = \frac{\mathrm{K}_{\mathrm{IC}}^{ini}}{K_{IC}^{un}} = 1 - \frac{K_{IC}^{C}}{K_{IC}^{un}} \quad (2)$$

2.2. Specimens and Tests procedure

In this research, in order to identify the effect of adding nano-silica on the fracture properties of the fiber-reinforced cementitious composite, five mixtures containing nano-silica in amounts of 1, 2, 3, and 4 percent by weight of cement were designed. Three beams with an initial notch and three cylindrical specimens were manufactured for each designed mixture. The dimensions of beams and cylindrical samples were 100x100x350 mm (width*height*length) and 100x200 mm (diameter x height), respectively. The notch of the beams had dimensions of 3x25 mm (width * height), was located in the middle of the beam, and was made by a plate during the manufacture of the specimen.

For identifying the fracture properties by applying the double-k model, the notched beams were subjected to a four-point bending test under displacement control loading. The loading rate was regarded to be 0.1 mm/min in accordance with the ASTM C1609. Moreover, the Slump flow test was applied to investigate the flowability of fiber-reinforced cementitious composite nano silica in its fresh state.

During the four-point bending test, consecutive images were captured by a DSLR camera to monitor the initiation and propagation of cracks in the specimen. Applying image processing, the values of crack mouth opening displacement (CMOD) corresponding to each stage of loading were found. The first cracking loads were detected by monitoring images using digital image correlation. This approach differs from others in that it is straightforward and inexpensive while also having a high degree of accuracy.

3. **Discussion and Results**

The most obvious findings to emerge from the experiments are as follows.

1. The addition of nano-silica decreased the slump flow of fiber-reinforced composite in the fresh state. This result may be explained by the fact that nano-silica particles have a high specific surface area.

2. The addition of nano-silica up to 3 wt% of cement improved the mechanical properties (i.e., compressive strength and flexural strength of FRCC's 28-day samples). In higher percentages of nano-silica, the mechanical properties decreased. A possible explanation for this result is that the agglomeration of nanoparticles leads to an adverse effect on the beneficial cooperation of nano-silica particles with other constituents of the cement paste.

3. By adding nano-silica up to 3 wt. % of cement, the initial cracking toughness, the fibers' bridging toughness, and the unstable fracture toughness increased. A significant result is that the increase in unstable fracture toughness can be considered mainly due to the increase in fiber bridging toughness rather than initial cracking toughness. This result supports the fact that adding an optimum percent of nano-silica causes an improvement in the interfacial interaction of polypropylene fibers with composite cement paste.

4. The addition of nano-silica up to 3 wt. % of cement decreased the brittleness number. A decrease in the brittleness number indicates an increase in the ductility of the composite. It can be inferred that better interaction between cement paste and fibers leads to improved ductility of fiber-reinforced cementitious composite.

4. Conclusions

The results of this study show that adding nano-silica up to the optimal percentage not only solves the disadvantages of current cementitious composites, such as delay in setting time but also improves the composite's mechanical behavior and fracture properties. Furthermore, it can be inferred that the brittleness is reduced due to the increased interaction between the fiber and the cement matrix.

5. References

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