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An investigation into fracture behavior of geopolymer concrete with digital image correlation technique

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HIGHLIGHTS

- DIC was proposed to monitor the crack tip field of fly ash based GPC.
- CTOD and crack extension length were achieved with the help of DIC.
- Crack growth behavior of fly ash based GPC was elaborated.
- Crack propagation can be evidently manifested in COD and crack extension length.

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ABSTRACT

Fly ash based geopolymer concrete (GPC) is gaining significant interest as a greener alternative to ordinary Portland cement concrete over the past decades. Its fracture behavior, especially the crack growth behavior, has received few attentions, possibly hindered by the difficulties in the monitoring of crack tip field with conventional measurement technique. Recently, digital image correction (DIC) has opened up the opportunity to gain a deep insight into its fracture behavior. Therefore, an investigation into the fracture behavior of fly ash based GPC with the use of DIC was performed. First, three-point bending tests on notched beam specimens were conducted. The displacement field of beam specimen was measured by DIC. Then, crack opening displacement (COD), crack extension length and mid-span deflection were achieved and the crack growth in fly ash based GPC were elaborated. Finally, the fracture energy and fracture toughness were calculated. The results show that DIC can be a useful technique for the monitoring of crack tip field. The crack propagation in fly ash based GPC can be evidently manifested in COD and crack extension length. The normalized crack extension length may be employed as a fracture criterion to pronounce the onset of unstable crack propagation in fly ash based GPC.

1. Introduction

Geopolymers, sometimes termed as "inorganic polymers", are cementitious materials synthesized by combining source materials which are rich in silica and alumina with strong alkali solutions and soluble silicates (in most cases) where the dissolved Al_2O_3 and SiO_2 species undergo geopolymerization to form a 3D amorphous aluminosilicate network [1]. Recently, they are gaining significant interest as a greener alternative to ordinary Portland cement (OPC). They can provide comparable or superior performance to OPC, such as high compressive strength, low shrinkage, acid resistance, fire resistance and low thermal conductivity, satisfying most of requirements for construction materials [2–4]. Furthermore, they are added with the advantage of environmental benefit as they completely move away from OPC and thereby the high CO_2 emission associated with its production. It was reported that the use of geopolymers could bring down the overall CO_2 emission by up to 60–80% in comparison with the use of OPC [5–9]. In addition, abundant of industrial byproducts generated in various industries, which are causing problems in term of finding an ideal solution for disposal purposes, were found to be suitable to use as geopolymer source materials. Therefore, the use of geopolymers offers the greatest potential in solving not only the environmental degradation related to the use of OPC as primary binder material in the construction industry, but also the waste management problems related to the aluminosilicate solid waste materials generated from various industries.

At present, fly ash and blast furnace slag appear to be the most promising precursors for large-scale industrial production of

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geopolymers [10,11]. Fly ashes are very fine residues from the combustion of coal during the operation of thermal power plants. There is an easy access to a suitable supply of fly ash as its annual production worldwide is estimated around 500 million tonnes [12–14]. In the past two decades, considerable research has been carried out throughout the world to cover the various aspects of fly ash based geopolymer, providing a large volume of useful data and important findings. For example, the properties of fly ash based geopolymer, such as compressive strength, splitting and flexural tensile strength, chloride resistance, sulfate resistance, acid resistance, thermal resistance, freeze-thaw resistance, and efflorescence resistance, have been studied extensively [15–17]. A wide variety of applications has also been identified for fly ash based geopolymer including geopolymer concrete (GPC), coating materials, fire resistant materials, adsorption and purification, and immobilization of toxic metals [17]. Among them, GPC has attracted most of the attentions. So far, GPC has been recognized as being equivalent to OPC concrete for non-structural applications by the state roads authority in Victoria, Australia in a 2010 update to their design specification Section 703 [18]. Researchers on the use of geopolymers have extended to the investigation of structural applications of GPC as well [19,20]. Furthermore, a few actual field applications of fly ash based GPC have been reported [21]. Therefore, the understanding that has been developed to date provides indications that fly ash based geopolymer does in fact have the potential for wide scale utilization in the construction industry, as well as in other niche applications.

Although fly ash based GPC has shown comparable or superior performance to OPC concrete in various aspects, it is still far from problem free. Like OPC concrete, most of fly ash based GPCs are also quasi-brittle in nature [17,22–24]. Because of the quasi-brittle nature, fly ash based GPCs are sensitive to cracking, which not only imposes constraints in their applications, but also affects their long term durability. Therefore, the fracture behavior of fly ash based GPCs, which is related to the formation and propagation of cracks, deserves intensive investigations to ensure their suitability for structural applications. Nevertheless, studies on fracture behavior of fly ash based GPC are still very limited in comparison with other mechanical properties. Pan et al. studied the fracture properties of low calcium fly ash based geopolymer paste and concrete with focuses on fracture energy and brittleness [22]. Sarker et al. investigated more fracture characteristics of low calcium fly ash based GPC, including fracture energy, fracture toughness, and fracture planes [23]. Recognizing that the curing method plays a significant role on the fracture properties of geopolymers, Nath and Sarker developed a low calcium fly ash based GPC, which is suitable for curing in ambient condition by adding a small percentage of ground granulated blast furnace slag (GGBFS), and evaluated the fracture energy and fracture toughness of the GPC [24]. Likewise, the incorporation of OPC in high calcium fly ash based geopolymer was suggested to improve the strength development of geopolymer cured at ambient temperature, and the fracture properties of fracture energy and fracture toughness were examined correspondingly [25]. In addition, studies on fracture properties of fiber reinforced fly ash based GPC have also been reported [26–28]. In all those previous studies, mainly two fracture properties, i.e., fracture energy and fracture toughness, were determined for fly ash based GPC, while the crack growth behavior of fly ash based GPC have received much less attention. The reason possibly lies in the fact that the monitoring of strain and displacement fields near the crack tip through conventional contact measurement techniques is very difficult if not impossible. For instance, there have been a number of attempts to use different techniques such as strain gauge, clip gauge to measure crack opening displacement (COD), which usually require the crack position known prior. In reality, however, this is not always the case, making them unworkable sometimes. Therefore, it is desired that new technique suitable for the monitoring of crack tip field be proposed so as to achieve a full understanding of the facture behavior of fly ash based GPC, especially its crack growth behavior.

Recent years have seen a great development in full-field optical measurement methods [29,30]. Among them, digital image correction (DIC) has emerged as a practical tool in the experimental mechanics. DIC uses the digital images of the surface of the object before and after deformation to obtain the displacement field of the object. A matching algorithm is employed to recognize and track a specific subset (a group of pixels) on a series of images. The concept behind the matching algorithm is that the distribution of grey values in a subset of the image taken at the undeformed state corresponds to the distribution of grey values of the same subset on the image taken at the deformed state. By tracking the subsets in each successive image and using photogrammetric principles of triangulation and bundle adjustment, the 3-D position or coordinate of each subset across the surface of the object are obtained and thereby the resulting relative displacements and strains can be calculated. For this technique work well, an arbitrary speckle pattern that is randomly sprayed onto the object surface or that is offered by the texture of the object's material is needed. The objective is to obtain an image with a varied and distinctive pattern, in order to enable discrimination between different subsets. DIC technique was developed in the 1980s independently by Yamaguchi [31] and Peters and Ranson [32]. But the technology has only recently been exploited in industry and research, benefiting from the availability of high resolution digital cameras as well as the rapid developments in image correlation algorithms. The technique is currently being explored to study the fracture behavior of some materials and can provide a wealth of additional information that was previously unobtainable [33–37]. To the best of the authors' knowledge, the use of DIC for the study of fracture behavior of geopolymers has not been reported yet. Recognizing the demand for more studies on fracture behavior of fly ash based GPC, as well as the opportunity offered by DIC to gain a deep insight into it, this study therefore performs an investigation into the fracture behavior of fly ash based GPC with the help of DIC. First, three-point bending tests on notched beam specimens of fly ash based GPC were conducted. To parenthetically examine the effect of notch depth on the fracture behavior of fly ash based GPC, beam specimens with same dimension but different notch depths were tested. DIC was employed to measure the displacement field of beam specimen throughout the test. Then, the crack mouth opening displacement (CMOD), crack tip opening displacement (CTOD), and crack extension length, which are not readily available through conventional measurement techniques, were achieved with the use of the displacement field measured by DIC. Upon them, the crack formation and propagation in the fly ash based GPC were elaborated. Finally, the fracture properties of fly ash based GPC namely fracture energy and fracture toughness were calculated and discussed.

2. Experimental program

2.1. Materials

Geopolymer binder was prepared with low calcium fly ash collected from a local thermal power plant in Wenzhou, China. In addition, GGBFS, which has been reported to be able to improve the workability and regulate the setting of the fly ash based GPC [17], was added as a small part of the binder. The chemical composition of fly ash and GGBFS determined by X-ray fluorescence (XRF) analysis are shown in Table 1. The alkaline liquid used was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3)