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Modelling of fracture strength of functionally graded geopolymer

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HIGHLIGHTS

- Functionally graded geopolymers were produced from two different types of fly ashes.
- Mathematical model for evaluation of fracture strength.
- Load direction with respect to graded region plays an important role.

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ABSTRACT

In the current paper, fracture strength of a functionally graded geopolymer was analytically modelled for crack propagation in two possible perpendicular situations with respect to the functionally graded region. Functionally graded geopolymer was produced by pouring and subsequent vibration of two layers of different alkali activated fly ash-based geopolymers into the moulds. The thickness of functionally graded region was determined equal to 18.6 mm through evaluating Si/Al ratio obtained from EDS. In modelling procedure of both crack configurations, the functionally graded region was considered to have 372 layers with the thickness of 50 μm and the fracture strength of the geopolymeric specimen in functionally graded region was related to the fracture strength of the constituent layers. To represent the variation of surface energy and elastic modulus in functionally graded region, three different functions including exponential, power-law and linear were considered. The obtained results from the proposed model show a good agreement with those of obtained through experimental procedure.

1. Introduction

The demands on acquiring reliable cementitious mixture for different operational conditions as well as the desire to their production with lower costs enforce scientists to survey into new concepts in concrete specimens. One possible method to improve the properties of concrete specimens in an affordable way is to produce “functionally graded concrete” (FGC) which for the first time was presented in 2006 [1].

In FGMs as multi-phase systems, to obtain unique mechanical, thermal and electrical properties, the composition changes gradually in some directions. They are distinguished in this way from the conventional composites that have discrete and piecewise nature as well as sharp interfaces [2]. The main advantage of gradual change in the graded region is reduction of stress concentration. Additionally, by arranging the appropriate constituent materials, one may access the required property that unattainable not only by a homogenous material, but by a complicated laminate composite. Finally, delamination which is caused during crack propagation into composite structure does not occur in FGMs [2,3]. Although delamination may increase the fracture energy of the composite materials with respect to FGMs, this behaviour is avoided in concrete structures where homogeneity and continuity of a specific cementitious section are of the main importance.

Wen et al. [1] examined two kinds of single-layer concrete specimens and functionally gradient structure concrete with three different Surface-layer thicknesses against rapid chloride attack and accelerated steel bar corrosion tests. They found that FGC system is able to improve resistance to chloride attack and hence reduce the corrosion of the incorporated steel bars. Dias et al. [4] statistically analysed different designs to choose formulations and present ideas for the production of functionally graded PVA fibre cement components. Through grading PVA fibres, they obtained affordable concrete with reduced total fibre volume without a significant decrease on modulus of rupture of FGC. Shen et al. [5] examined flexural strength of four-layer functionally graded fibre-reinforced cement concrete by changing the content of PVA fibres in the layers. Fibre volume fraction was linearly changed from 0% in the compression zone to 2% in the tensile zone. The results show 50%

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improvement in flexural strength as well as comparable fracture energy with respect to homogeneous PVA fibre-reinforced concrete with same volume fraction of PVA fibres. Quek et al. [6] developed functionally graded polyethylene fibre-reinforced concrete specimens for resisting to high velocity impact tests. The results showed that FGC specimens have superior impact energy with respect to the normal concrete. This short review indicates the abilities of functionally graded concrete systems to improve the required properties affordably. Hence, functionally graded geopolymer (FGG) specimens may act in a similar way as well.

Geopolymers (alkali activated binders), eco-friendly materials with much lower CO_2 emissions produced from different sources such as fly ash [7–9], slags [10–12] and metakaolin [13], individually or together, are considered as the main possible substitution materials of ordinary Portland cement- (OPC)-based concrete. The most attractive constructional raw material for geopolymer production is fly ash because of its availability and cheaper price. Fly ash-based geopolymers are made from mixtures of fly ash as aluminosilicate source and a regular silica-rich alkali activator which normally is a combination of sodium silicate or potassium silicate together with sodium hydroxide or potassium hydroxide [7–9]. In the current study, FGG structures are introduced to attain unique mechanical properties that could not be obtained by a single homogenous geopolymer or even geopolymer composite. Development of FGG structures in the future will deliver reasonable compressive, flexural and splitting tensile strength with the other demanded properties that are not wholly achieved in a homogeneous cementitious material.

The aim of the present study is to model fracture strength of the proposed fly ash based FGG structure for cracks perpendicular to the functionally graded region. Two individual models were presented that in both of them, the fracture strength of the specimen was considered as the sum of the fracture strength of homogeneous layers together with the constituent layers of functionally graded region.

2. Experimental procedure

Two fine fly ashes with the particle size distributions obtained by ASTM C115 [14] standard illustrated in Fig. 1 and chemical compositions given in Table 1 were considered for this study. The average particle size of fly ash type I and type II were 14 and 9 μm respectively. Alkali activation was done by a mixture of sodium hydroxide (NaOH) and sodium silicate. The concentration of NaOH was 14 M and sodium silicate was used as-received. High NaOH concentration causes higher strengths due to more convenient dissolution of Si^{4+} and Al^{3+} from fly ash to alkali activator [15], and hence to reduce the possibility of weakening the aluminosilicate structure as well as reducing the scattered data. The chemical composition of sodium silicate has been given in Table 1. Sodium silicate to NaOH weight ratio in alkali activator was considered 2.5 for both geopolymeric mixtures since this ratio is used in a considerable number of geopolymer-related works reported in the literature [16].

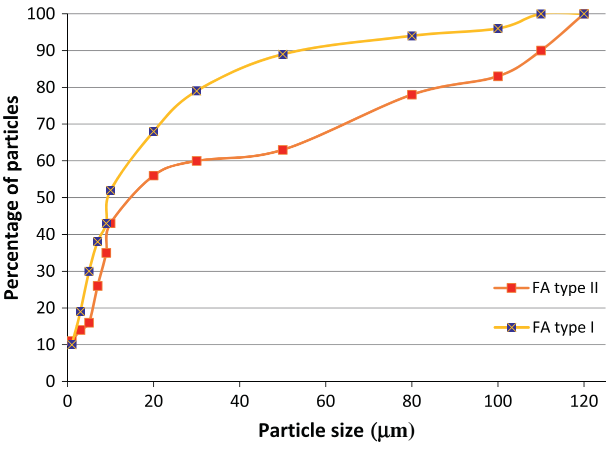

Fig. 1. Particle size distribution of fly ashes type I and II.

Table 1
Chemical composition of the utilized fly ashes and sodium silicate.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O	L.O.I.
FA type I	35.2	23.2	12.3	20.1	2.3	0.3	3.4
FA type II	62.7	22.1	2.5	3.1	0.5	0.4	2.6
Sodium silicate	37.8	–	–	–	–	12.3	–

Two geopolymeric pastes were prepared. The first (G1) was made by mixing 3:1 fly ash type I and alkali activator weight ratio. The second geopolymer (G2) was made in same procedure but by using fly ash type II.

To make FGG structure, geopolymers mixtures were poured in two layers. The mould was half-filled by G1 mixture and vibrated for 45 s to avoid air bubbles. After that, G2 was poured as the top layer and again vibrated for 45 s to avoid air bubbles as well as to provide diffusion of G1 and G2 mixtures into each other. The vibration was carried out on a vibration table by the frequency of 15 Hz. The reason for using a low frequency was due to reducing the possibility of mixing the whole pastes into each other. In pre-curing stage, the moulds were left for 24 h while covered with a polyester sheet. After 24 h, the specimens were de-moulded and were oven cured for 24 h at 70 °C and finally were cured for additional 27 days in room temperature. The method of production FGG structure has been illustrated schematically in Fig. 2.

To determine the boundary conditions required for modelling process, monolithic geopolymeric specimens were made from G1 and G2 mixtures. Both mixtures were made in the same manner mentioned for FGG structure where the two poured layers were similar.

To determine modulus of elasticity of the monolithic specimens, cylindrical samples with the diameter of 150 mm and the length of 300 mm were prepared and tested in accordance to the ASTM C469-87 [17].

Fracture strength of the FGG structure as well as monolithic specimens was acquired by a single-notched edge beam under three-point loading with the dimensions of 10 cm × 10 cm × 65 cm. The span to depth ratio was four and the width of crack was considered 5 mm with a crack tip radius of 1 mm. The width and radius of crack were selected in such way that have the minimum impact on abrupt crack propagation, and assure that the crack propagates from the demanded point.

Fig. 3 shows schematically the configuration of the cracks with respect to the functionally graded region. In the first configuration (which is called CP1 here) the crack is perpendicular to the graded region and incorporates the whole layers of this region. The crack propagates along the graded region. In the second configuration (which is called CP2 here) the crack is perpendicular to the graded region while propagates across the layers of the graded region. The similar structures to CP1 and CP2 in laminated composites with sharp interfaces are called crack divider and crack arrester configuration and may be considered as an indicative definition. However, dividing or arresting cracks are occurred during delamination of the

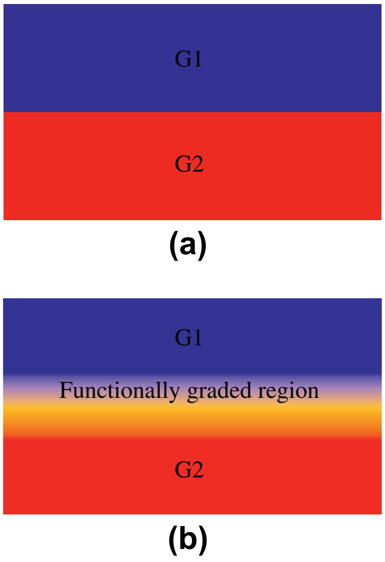

Fig. 2. Schematic illustration of the process for producing FGG structure, (a) supposed two different layers of geopolymers and (b) formation of functionally graded region during vibration and subsequent hardening.