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Modeling of fracture parameters for crack propagation in recycled aggregate concrete

Rajendra Kumar Choubey, Shailendra Kumar *, M. Chakradhara Rao

Department of Civil Engineering, Institute of Technology, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur (C.G.) 495009, India

HIGHLIGHTS

- Fracture parameters of RAC with varying RCA content are determined using FCM and DKFM.
- P_u and K_{IC}^{un}, K_{IC}^{ini} and P_{ini} of RAC decrease linearly with varying RCA content as predicted by FCM and DKFM respectively.
- The ratio P_{ini}/P_u and K_{IC}^{ini}/K_{IC}^{un} are almost constant for NAC and RAC with varying RCA content.

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ABSTRACT

The paper presents the applications of fictitious crack model and double-K fracture model, to determine the fracture parameters for crack propagation in recycled aggregate concrete with varying content of recycled concrete coarse aggregate. The required material properties for modeling applications are derived using various empirical relations, for the known values of compressive strength. The fracture parameters of normal and recycled aggregate concrete are determined and a systematic comparative study has been carried out. The outcome has revealed an interesting finding and thus it is concluded that these two conventional concrete fracture models can be implemented for the study of fracture behavior of recycled aggregate concrete with varying substitution of natural aggregate by the recycled aggregates.

1. Introduction

The global concrete industry uses approximately 10 billion tons of sand and rock annually, which makes it the largest consumer of natural resources in the world [1]. Use of the aggregate wreckage from old concrete structures is the need of these days to reuse them as recycled coarse aggregate for the production of new concrete. This practice will be conducive for the environmental preservation and sustainable development. Thus, it is now considered as an alternate concrete aggregate material source yielding a positive socio-economic impact. Researchers have been engaged in experimental investigations with regards to the mechanical properties and durability characteristics of recycled aggregate concrete (RAC), to ascertain the utilization of waste concrete aggregate by substituting the natural aggregate, in construction. Although significant research work has been carried out on the mechanical properties of RAC, but study on crack propagation and fracture parameters of RAC is meager in the literature.

Casuccio et al. [2] put forward from their experimental investigation, that recycled concrete aggregate (RCA) present in RAC slightly lowers the strengths (1–15%), lowers the modulus of elasticity (13–18%) and significantly reduces the fracture energy (27–45%) and, consequently affects the fracture zone size, when it is compared with a concrete prepared with natural coarse aggregates. Reis and Jurumenh [3] have investigated the influence of replacement of fresh sand by recycled foundry sand on fracture properties of polymer concrete. The results showed that epoxy polymer concrete made with recycled foundry sand has higher fracture toughness and slight lower fracture energy when compared with fresh sand polymer concrete.

A comprehensive review of the findings in China during the past decade, related to influences of the RCA on mechanical and fracture properties, has been presented by Xiao et al. [4]. In the study, it is reported that the compressive, tensile and shear strengths of RAC are generally lower than those for conventional concrete and these values decrease with the increase of RCA contents. The modulus of elasticity of RAC reduces with increase in RCA content; however the peak strain is larger than that of conventional concrete. The RCA content has a significant influence on the stress–strain curve

* Corresponding author.
E-mail address: shailendrakmr@yahoo.co.in (S. Kumar).

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of RAC in uni-axial compression, tension and shear. The RCA replacement percentage has nearly no influence on the bond strength between RAC and deformed rebar, while the bond strength between RAC and plain steel rebar decreases with the increase of RCA content. RAC behaves in a more brittle manner than conventional concrete in compression and the plastic deformation is less. Li et al. [5], reported in their study, that the mechanical properties of new mortar matrix and the corresponding new interfacial transition zone play a significant role in overall stress–strain response and fracture process of modeled recycled aggregate concrete. The finite element method (FEM) modeling is capable of simulating the complete stress–strain curve and also the overall fracture patterns including localization of deformation and the micro-crack pattern. Arezoumandi et al. [6], determined fracture energy from the experiments using five mixes with 0%, 30%, 50%, 70%, and 100% recycled concrete aggregate as a coarse aggregate replacement in concrete. The authors compared these results with different design codes and analytical equations and reported that, the values obtained from the CEB-FIP Model code-2010 [7] and Bažant equations [8] have a good agreement with the test results and the JSCE-07 [9] provision is found to underestimate the fracture energy for all specimens. The outcome of the study conducted by Riaz et al. [10], indicates that the mechanical properties of RAC starts degrading when recycled aggregates (RA) replacement level exceeds 25% and degradation further increases with the increase in the replacement level. The compressive strength and static modulus of elasticity is found to decrease with an increase in RCA content and a maximum decrease of 20% is observed corresponding to 100% replacement. A gradual decrease in value of fracture energy in tension is observed with increase in percentage of RA with a maximum drop of 38% when RCA replacement in concrete is 100%. However, fracture energy value in tension did not alter with concrete containing 25% RA, whereas fracture energy in compression was significantly reduced, i.e., 24% reduction in fracture energy was observed with concrete containing 25% RA. Maximum reduction of 45% in the value of fracture energy in compression was exhibited by the concrete made with 100% RA. The peak load value in flexure is noticed to be decreased by replacing the natural aggregates with RCA, however, the crack mouth opening displacement (CMOD) value at the peak load in flexure remains almost unchanged.

The main reasons for reduction in strength, elastic property and fracture energy for RAC are increased concrete porosity, weak aggregate matrix interface bond in the new matrix due to residual adhered-mortar on RCA. The prime factor affecting the elastic modulus of RAC, is the modulus of elasticity of RCA itself, as it is more prone to deformation than the material aggregates.

From the existing literature review it is observed that, extensive research work on mechanical and durability characteristics of RAC have been carried out. Also much of the experimental and numerical studies on the crack propagation and fracture properties for normal aggregate concrete have been carried out worldwide using various concrete fracture models. However, experimental and numerical studies on crack propagation and fracture properties of RAC are meager in the literature. It is also observed that, few experimental results are reported in the literature, on the studies of fracture behavior of RCA and no study has been reported on fracture behavior of RAC using conventional concrete fracture models.

In order to determine the critical stress intensity factor of concrete, the concept of linear elastic fracture mechanics (LEFM) was first applied to concrete notched beam by Kaplan [11]. Thereafter, extensive research and studies for crack propagation and fracture properties of concrete like materials have been carried out. It is now clear that the concept of LEFM cannot be applied directly to concrete and concrete like materials, because a sizeable fracture process zone exists ahead of the initial crack tip. Then many nonlinear fracture models have been developed and applied to concrete structures by various researchers. These nonlinear models are: cohesive crack model (CCM) or fictitious crack model (FCM) [12–26]; crack band model (CBM) [27], two parameter fracture model (TPFM) [28], size effect model (SEM) [29], effective crack model (ECM) [30]; K_R-curve method based on cohesive force distribution [31–34], double-K fracture model (DKFM) [26,32,35–50] and double-G fracture model (DGFM) [51]. Among these eight models, FCM and CBM are based on numerical approach, in which fracture energy is required as one of the input parameters. But, for the remaining models, either the analytical or semi-empirical and semi-analytical formulae in the modified form of LEFM are used in the form of stress intensity factor or fracture energy, to express the fracture toughness of concrete.

Hillerborg et al. [12] initially applied fictitious crack model (FCM) as a suitable nonlinear model for mode-I fracture, to simulate the softening damage of concrete structures. The authors showed that, the analysis of crack formation, crack propagation and failure analysis can be done with fictitious crack model, even if coarse finite element is used, thereby eliminating the mesh sensitivity. This method is a simplified nonlinear fracture model, which can simulate satisfactorily the complex nonlinear phenomena in the fracture process zone of concrete and it predicts the localized real physical behavior in the vicinity of a crack and at the crack tip. With these advantages, the FCM has become more popular in its implementation. Extensive experimental and numerical studies based on fictitious crack model have been carried out by many researchers [12–26]. The model is based on the assumptions that: (i) the bulk of material behaves in a linear elastic and isotropic manner, (ii) the cohesive process zone begins to develop when the maximum principal stress becomes equal to the tensile strength and (iii) the material is in partial damaged condition and is still able to transfer the stress known as cohesive stress after the formation of cohesive fracture zone. The cohesive stress depends on the crack opening displacement. For development of the model three material parameters i.e., modulus of elasticity E, uni-axial tensile strength f_t, and fracture energy G_F along with stress-displacement softening relation are required.

The three important stages of crack propagation in concrete i.e., crack initiation, stable crack propagation and unstable fracture in concrete can be well described by DKFM among all the concrete fracture models based on modified LEFM principle. The method does not require the closed loop testing system in the laboratory and is characterized by two material parameters viz initial cracking toughness K_{IC}^{ini} and unstable fracture toughness K_{IC}^{un}. The initiation toughness is defined as the inherent toughness of the materials, which holds for loading at crack initiation when material behaves elastically and micro cracking is concentrated to a small-scale in the absence of main crack growth. The total toughness at the critical condition is known as unstable toughness K_{IC}^{un} which is regarded as one of the material fracture parameters at the onset of the unstable crack propagation. Extensive numerical and experimental studies have been carried out by the researchers around the world [26,32,35–50] on the behavior of double-K fracture parameters of concrete using varied tests configurations and material properties.

It is obvious from existing literature that the strength and elastic properties of RAC gets influenced with the amount of RCA content and crack propagation study on fracture parameters of RAC is meager in the literature. Thus it is worth, to carry out a systematic study, on fracture parameters of RAC. Hence, the aim of the present paper is to investigate the application of concrete fracture models i.e., FCM and DKFM for predicting the fracture parameters of RAC with varying RCA percent replacement in conventional concrete. Also, the characteristics of fracture parameters predicted by DKFM