Cement and Concrete Composites 93 (2018) 1–18

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Experimental investigation of compressive strength and compressive fracture energy of longitudinally cracked concrete

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ARTICLE INFO

Keywords:
Compressive strength
Compressive fracture energy
Cracked concrete
Coarse aggregate size
Crack width

ABSTRACT

In this study, compression tests of longitudinally cracked concrete were conducted to clarify the effect of existing crack on reduction of compressive strength and compressive fracture energy. In the specimens, one or two longitudinal cracks were introduced mechanically before compression loading. The experimental parameters were set to specimen shape, size, height to diameter ratio, coarse aggregate size, number of existing crack and the width. Based on experimental evidences, it was clarified that the reduction of both compressive strength and compressive fracture energy due to existing crack was dependent on crack width and those reduction tendencies are clearly influenced by coarse aggregate size without the effect of other parameters. Moreover, in order to discuss the reduction mechanism, compression tests focused on the effect of crack shape such as wave height and length were also conducted. In the specimens, imitation of existing cracks were embedded for neglecting the effect of damage near crack. As a result, it was found that the crack shape was significant for the reduction of concrete strength and compressive fracture energy. Finally, compressive strength reduction model in association with maximum crack width and maximum coarse aggregate size was proposed.

1. Introduction

Compressive strength and compressive fracture energy are one of the most important mechanical characteristics of concrete structures. These values are generally determined by uniaxial compression test using 'no-damaged' concrete specimen. However, several mechanical function and/or environmental factors have affected concrete structures and those effects appear as existing cracks. Hence, to evaluate and predict the change in structural performance, it is definitely necessary to clarify the influence of existing crack against compression strength and compression fracture energy.

Collins et al. [1] and Miyahara et al. [2] attempted to clarify the change of compressive strength in plate like members which had axially distributed cracks. Based on the experimental results, the equations of reduction of compressive strength of cracked concrete were proposed using averaged strain index. It has been widely used for finite element method with smeared crack approach and has contributed advancement and improvement of concrete structural analysis. However, this model did not take into account for the influence of non-uniformly distributed cracks and/or few dominant cracks observed in RC column and beam.

Researchers like Van Mier [3], Lertsrisakulrat et al. [4] and Nakamura et al. [5] have tried to determine the compressive fracture energy experimentally. Nakamura et al. [5] observed that local compressive fracture energy, which doesn't include elastic energy at no fracture zone, is independent of size and geometry of specimen and it can be described only by compressive strength, and they proposed the model for compressive fracture energy as a function of compressive strength. In Markeset et al. [6] a Compressive Damage Zone model is proposed describing the compressive failure as combinations of distribute tensile splitting cracks and a shear sliding failure within a damage (fracture) zone of limited length. Based on Nakamura's model, the analytical accuracy of post peak behavior of RC structures using FEM was improved a lot (Cervenka et al. [7]). However, the compressive fracture energy was obtained by using 'no-damaged' concrete specimen and the effect of existing cracks on compressive fracture energy is yet unknown.

The compressive failure of concrete has often been observed at cracking area. Therefore, it is necessary to comprehend the relationships between existing cracks and compressive fracture energy as same as compressive strength of cracked concrete. In addition, Sangha et al. [8], Kozul et al. [9] and Van Mier [10] concluded that, both of compressive strength and compressive fracture energy could be affected by the size of coarse aggregate. Liu et al. [11] observed that the fracture

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https://doi.org/10.1016/j.cemconcomp.2018.06.015
Received 22 December 2017; Received in revised form 19 June 2018; Accepted 22 June 2018
Available online 23 June 2018
0958-9465/

process under compressive stress starts from micro cracking in the interfacial area of aggregates. In addition, Zaitsev and Wittmann [12] pointed that the fracture process can be changed in association with strength of paste. On the other hand, meso scale structural analysis was applied to this problems by Nagai et al. [13] in order to comprehend the fracture behavior of interface between coarse aggregate and mortar under multi-axial stress. Thus, aggregates can influence the compressive fracture process, however the mechanism is still not clear.

Although reduction of compressive strength was modeled by using average strain, the applicability of introducing the concept of averaged strain to numerical analysis should be paid attention. That is, when evaluation formula based on averaged strain index is applied, element size effect of strain due to localization problem of softening materials appears and the strain values cannot be decided uniquely dependent on element size. Hence, the value of numerical model based on average strain is also influenced by element size and it is difficult to define the compressive strength using the value of averaged strain.

The goal of this study is to clarify the reduction behavior of compressive strength and compressive fracture energy of longitudinally cracked concrete. In order to achieve the goal, compression tests were carried out using cylindrical and prism specimen in which parameters such as number of existing crack, geometry of specimen, height to diameter (H/D) ratio and coarse aggregate size were altered. Furthermore, the compression tests of concrete specimens embedded by imitation crack, which control the crack width and crack shape such as crack wave height and length, were carried out. The reduction mechanism of compressive behaviors due to existing cracks was investigated. Finally, a model of compressive strength reduction in association with maximum crack width and maximum coarse aggregate size was proposed.

2. Compressive behaviors of longitudinally cracked concrete affected by several influence factors

The effect of existing longitudinal crack, which were introduced mechanically, on compressive behavior was investigated by uniaxial compression test including post peak behavior. Colins et al. [1] and Miyahara et al. [2] investigated the effect of existing crack parallel to compressive force by panel type specimens having distributed cracks. The feature of current study is that specimens are cylinder and prism with solid shape and number of existing cracks are one or two. In this study, the target existing cracks are the dominant cracks, which distribute non-uniformly and observed in solid concrete structures such as column and beam.

2.1. Experimental overview

Experimental arrangement along with the state of the specimen utilized in this study are shown in Table 1.

Experimental conditions as shown in Table 1 can be summarized as follows: (1) cylindrical sample (φ 100 mm, φ 200 mm), prism sample (100 × 100 mm), (2) height to depth ratio (H/D): 2, 3, 4: D = 100, 150 mm, (3) Coarse aggregate size: 5–10, 15–20 mm, (4) existing crack number: 0, 1, 2. Moreover, existing crack width was varied by controlling loading when the crack was introduced. There are two test series. Series 1 investigated the effect of factors (1), (2) and (4) on compressive strength and compressive fracture energy. Series 2 mainly focused on factor (3), the effect of maximum aggregate size. The mix proportions of concrete are shown in Table 2. Although two kinds of mix proportion were used, target compressive strength was about 40 N/mm^2.

The existing cracks were introduced by applying splitting tensile tests as shown in Fig. 1. It is clear from Fig. 1 that, the cylindrical specimens were sandwiched in between steel plates when load was applied to spherical steel ball, placed on top of steel plate. On the contrary, rectangular specimens were sandwiched in between steel bars when load was applied to steel plate, placed on top of steel bars. When two longitudinal cracks were introduced to specimen, second crack was introduced in the direction perpendicular to first crack as shown in Fig. 1. It is noted that completely separated specimens during the introduction of existing cracks excluded from the present study. This is one of the reasons why the number of specimens are different in different case as shown in Table-1. After introducing the cracks, existing crack width was determined by crack scale as shown in Fig. 2.

As depicted in Fig. 2, Crack width was measured at about every 50 mm from top to bottom of specimen on the cracked surface. In this study, crack width was evaluated by three definitions such as average crack width (w_a), total crack width (w_{sum}) and maximum crack width (w_{max}). The average crack width (w_a) is the average value of all measuring points while the total crack width (w_{sum}) is calculated by average crack width multiplied by crack number, and the maximum crack width (w_{max}) is the largest average crack width in a surface.

After measuring crack width, compression tests were conducted. High stiffness universal testing machine with a maximum loading capacity of 2000 kN, was used for this experiment. The compression testing condition is shown in Fig. 3. It is known that the fracture behavior under compressive stress is strongly influenced by loading condition such as boundary condition and loading speed (Vonk [14]). In order to reduce the friction between specimen and loading/supporting plate, two Teflon sheets with a thickness of 0.05 mm each having glued together by silicone grease were set to top and bottom of specimen. The compression load was controlled with a loading speed of 0.4 ± 0.6 N/mm^2/sec as per JIS A 1108, 2006 guideline. After peak load, the loading and unloading cycle was applied to concrete specimen. Unloading was set until the specimen reaches 20% of peak load as shown in Fig. 4. Ultimate state was defined by the 20% of peak load.

In order to measure deformation of specimen due to compression loading, four displacement sensors were set in between loading plate and supporting plate as shown in Fig. 3. Deformation of specimen was computed as the average of the displacement readings obtained from displacement sensors. Strain was calculated as the average displacement of specimen divided by specimen length. The accuracy of strain determined by these displacement sensors before peak load was verified by strain gauges, which length is 60 mm. Since, Teflon sheets were used to reduce the constraint effect of edge of specimen the value of strain gauges can be compared with averaged strain of displacement sensors due to almost uniform strain distribution before peak load. As shown in Fig. 4, it was confirmed that the strain measured by displacement sensors were in good agreement to that of strain gauge results. In fact, some of the load-displacement curves indicated lower initial stiffness. Then, the measuring point, which had maximum gradient of tangential line in the range of 20% of maximum load, was searched and the vertex of the tangential line with x-axis was set to original point. Moreover, the results were not adopted when the difference of four displacement sensors was larger than 0.2 mm. This is another reason of different number of specimens required for different case as shown in Table 1. Envelope stress-strain curve was extracted from whole stress-strain curve by utilizing the experimental results. Due to brittle failure of some specimen, during loading cycle beyond peak load, the number of specimen was different in between peak load and ultimate state.

In reference to Nakamura et al. [5] compressive fracture energy can be defined as the area of absorbed energy represented by the load displacement curve due to compression load divided by the cross section of specimen. Using this method, compressive fracture energy was calculated from the area under load-displacement curve by deducting the area of first cycle of loading until peak load. The reason of deduction is to ensure that only region of plastic energy under the load displacement curve is taken care of. The detail of calculation of compressive fracture energy is depicted in Fig. 5.

Compressive fracture energy was estimated by the empirical model proposed by Nakamura et al. [5] and Lertsrisakulrat et al. [4] as shown in eqs. (1) and (2). According to those models, compressive fracture