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Investigating the effects of maximum aggregate size on self-compacting steel fiber reinforced concrete fracture parameters

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HIGHLIGHTS

- The effects of maximum aggregate size and steel fiber volume on fracture behavior of SCC were studied.
- The largest aggregate size of 12.5 mm can be appropriate for SCSFRC concrete.
- Fracture properties of SCSFRC were obtained using two different methods using Work fracture method and Size effect method.
- Size effect method can predict the peak load with a good precision for SCSFRC beams.

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ABSTRACT

This research has studied the effects of maximum aggregate size of coarse aggregate and volume fraction of steel fibers on the parameters of self-compacting concrete fracture/brittleness. The laboratory program was implemented and the percent fiber and aggregate size were considered variable. Accordingly, 9 mix designs were prepared in 3 series based on 0.1, 0.3, and 0.5% steel fiber and three aggregate sizes (9.5, 12.5, and 19 mm) were considered in each fiber series. A total of 108 different-size notched beams were then prepared and fracture parameters were studied using Work Fracture Method (WFM) and Size Effect Method (SEM). Results have shown that in both methods, the largest aggregate size of 12.5 mm can be appropriate for self-compacting steel fiber-reinforced concrete(**SCSFRC**), although it is more significant in work fracture method. With the increase of aggregate size to 19 mm, G_F and L_{ch} decrease in work fracture method. However, in size effect method the concrete will be more ductile if V_f is increased, and it will be more brittle if d_{max} is increased. Comparing to the size effect method, the work fracture method performed better in energy absorption with the increase of both aggregate size and the steel fiber percentage. Size effect in such concrete with different fiber percentages was as anticipated and G_F/G_f ratio was found 8.89.

1. Introduction

Nowadays, concrete is a very important and highly applicable material in industry and its ductility and ductility in mold and its strength variations with varying percentages of cement, aggregate, water, and additives have made it a very popular material for designers. However, it has weaknesses as well; low tensile strength, post cracking potential, brittleness/ductility, fatigue capacity, and impact strength are among the ones that need enhancement.

To improve some of the above mentioned weaknesses, use of fiber in concrete has become quite popular and fiber concrete is now widely used in the construction of sidewalks, roads, parking lots, airports, and tunnels [1,2]. Using steel fibers in concrete (SFRC) improves its tensile and bending strength, energy absorption, and ductility, but the effect depends on the type, volume, direction, and distribution of fibers in the fracture surface [3–5]. These **SFRC** features can play important role in the structure's economical concrete technology and materials; energy absorption and concrete reinforcement can effectively reduce concrete fracture risk [6].

Self-compacting concrete has good workability; it flows easily between reinforcement bars in the mold under its own weight without aggregate segregation and needing any vibration [7]. Using steel fibers in self-compacting concrete (SCSFRC) and studying its details have been reported by many researchers. Siddique et al. [8] showed that in fly ash-improved self-compacting concrete (SCC), an increase volume fraction hooked-ends steel fibers will increase tensile and bending strength of **SCC** with 0.5 and 1% steel

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fiber can have an acceptable workability. Beygi et al. [6] studied the effects of three types of fibers (steel fibers, propylene, and glass) and nano-silica on **SCC** and showed that an optimal use of fibers and nano-silica can improve its mechanical properties; Ferra et al. [9] reported similar results too. Madandoost et al. [10] studied the mechanical behavior of SCC under the effects of varying cements (400, 450, and 500 Kg/m^3) and different steel fiber percentages ($V_f = 0, 0.38, 0.64$, and 1%) with two maximum aggregate sizes ($d_{max} = 10$ and 20 mm) and showed that an increase of d_{max} increased the compressive strength, but an increase in the fiber volume decreased it. Alberti et al. [11] showed that in normal vibrated concrete (NVC) and **SCC** reinforced with polypropylene fibers 60 mm long, an increase in fiber reduced compressive strength and modulus of elasticity, but increase the tensile strength.

A change in any concrete element such as aggregate size, volume, type, cement, and water-cement ratio (W/C), or adding such additives as fly ash, nano-silica, or fiber can affect its mechanical, rheological, and specifically, its fracture behavior leading to a different crack behavior; this has been reported by many researchers [15–21]. Beygi et al. [15] showed that in **SCC**, an increase in aggregate size, increased fracture energy, characteristic length (L_{ch}) and length of fracture proses zone (C_f). They also stated when decrease water to cement ratio from 0.7 to 0.35 increase fracture energy, decrease L_{ch} from 427 to 251.1 mm and C_f from 29.1 to 14.1 mm [20]. Karamloo et al. [19] studied the effects of aggregate size in self-compacting concrete with light aggregates (SCLC) and showed that an increase in size increased the **SCLC** fracture energy. Alyahya et al. [21] reported similar results too and showed that an increase in aggregate size increased the fractal dimension.

In fiber reinforced concrete, cement and aggregate size/volume are not the only parameters that affect the properties of the newly hardened concrete; length, diameter, type, length-to-diameter ratio (l/d), and amount of fiber too play vital roles [10]. Adding fiber to cement matrix prevents the crack growth and makes the matrix more ductile; since concrete brittleness is a measurable parameter (when effect of size is studied), adding fibers can vary this parameter.

Size effect shows its importance when one attends to interpret the behavior of real structures through small laboratory prototypes. Since the affected area of the crack tip can have linear or nonlinear behavior depending on the structure size, Bazant proposed some specific criteria (low-size effects) needed for such studies [22,23]. Researches on size effects and fracture energy are many [15,19,20], but those performed in recent years show that adding fiber to concrete affects all the features of the newly hardened concrete and require more studies. Yoo et al. [24] showed that using fiber in high strength concrete reduces size effect compared to **NVC**. Sahin & Koksal [25] studied the effects of different fiber types and volumes on high strength concrete and concluded that fiber volume had considerable effect on the tensile strength and characteristic length parameter.

This research aims to study the fracture parameters of self-compacting steel fiber-reinforced concrete and to show that adding steel fibers to the latter as a new material in the mix design will vary the fracture matrix and will cause changes in the fracture energy; in other words, we are going to study the fracture energy variations with the changes in maximum aggregate size (d_{max}) and volume fraction of fiber (V_f) in **SCC** which is flow-able, does not need vibration, and fiber distribution in it is quite random. Studies and their related results have revealed that information on the use of fiber in **SCC** is still insufficient and more studies are required in this regard. This paper has analyzed the fracture parameters using size effect method and work fracture method in a laboratory work.

2. Calculating fracture parameters

2.1. Work fracture method

For the first time, Hilerborg [26] proposed the fictitious crack model wherein the fracture energy (G_F) is found as follows:

$$G_F = \frac{\int Pds}{b(w-a)} \tag{1}$$

where a is the initial crack length in the beam under three-point bending, w is the specimen width, b is its thickness, and $\int Pds$ is the total area under load–displacement curve. Earlier studies [10,11] have shown that adding fibers can hardly enhance the compressive strength (it sometimes even reduces it), but the main reason for this adding is to improve the concrete post cracking ductility strength behavior. Accordingly, to better indicate the fiber concrete behavior and energy absorption, notched beams based on RILEM TC-189 SOC [27], ASTM 1609 [28], and RILEM TC-50 FMC recommendations [29] have been used.

To show the material brittleness or ductility, Hilerborg introduced another parameter called characteristic length (L_{ch}) as follows:

$$L_{ch} = \frac{EG_F}{f_t^2} \tag{2}$$

where E is the modulus of elasticity, f_t is the tensile strength, and G_F is the fracture energy. A high L_{ch} is an indication of concrete ductility and higher crack strength and vice versa.

2.2. Size effect method

Using the fracture parameters for concrete and semi-brittle materials, Bazant and Pfeiffer [22] presented the size effect theory through a specific method as follows:

$$\sigma_N = \frac{B}{\sqrt{1+\beta}} \qquad \beta = \frac{d}{d_0} \tag{3}$$

where β (introduced by Bazant-Kazemi [23]) shows the brittleness number and B and d_0 are experimental parameters found as follows using regression analyses and considering the peak load for different-size specimen:

$$\begin{aligned} &Y = AX + C \\ &X = d \quad Y = \left(\frac{1}{\sigma_N}\right)^2 \quad d_0 = \frac{C}{A} \quad B = \frac{1}{\sqrt{C}} \end{aligned} \tag{4}$$

Considering the above relations, such parameters as fracture energy (G_f), effective length of process zone (C_f), and fracture toughness (K_{IC}) can be determined as follows:

$$G_f = \frac{g(\alpha_0)}{AE} \tag{5}$$

$$C_f = \frac{g(\alpha_0)}{\acute{g}(\alpha_0)}\frac{C}{A} \tag{6}$$

$$K_{IC} = \sqrt{E\,G_f} \tag{7}$$

where $g(\alpha_0)$ and $g'(\alpha_0)$ are dimensionless equations of the rate of energy release, and A is the slope of line found by regression. All the above relations are fully presented in RILEM TC 89 [30] where in notched beams under three-point loading have been used and the mold width (b) is recommended must not be less than 3 times the largest aggregate size, but in ASTM 1609 [28], it is recommended that b should be at least 3 times the fiber length. Since