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Development of nomogram for the practical mix design of steel fiber reinforced concrete

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HIGHLIGHTS

- A practical mix design method called the mix design nomogram of SFRC was revealed.
- Revealed nomograms contain both workability and mechanical properties of SFRC.
- Nomograms specially include flexural strength and modulus of toughness of SFRC.
- Loss of time and material in the production process is expected to be reduced.

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ABSTRACT

Steel fiber reinforced concrete (SFRC) is a special type of concrete of which the use of this concrete type is growing up. With the wide using of SFRC, some requirements have emerged. One of these requirements is a practical mix design of SFRC. In this study, it is aimed to produce an effective mix design nomogram, including both fresh and hardened properties of SFRC, simultaneously. With this aim, the relationships between mixture proportions, fresh and hardened properties of SFRC were revealed with the convenient graphics, and these were brought together to create a nomogram. As different from previous studies, two most important superior mechanical properties of SFRC such as flexural strength and modulus of toughness were included in the developed mix design nomogram. As a conclusion, two nomograms which help to accurately and practically estimate mix design of SFRC with aimed properties were revealed. Using these nomograms, at academic milieu and institutions for SFRC, it can be possible to minimize loss of material and time during trial-and-error sample production. Thus, the production process of SFRC can be achieved more practically and economically.

1. Introduction

As a composite material, steel fiber reinforced concrete (SFRC) is produced to increase ductility of the traditional concrete which has low tensile strength, flexural strength, and impact resistance compared to its sufficient compressive strength [1,2]. SFRC is described in the literature as the concrete that contains a mixture of cement, water, fine and coarse aggregate and fibers made of steel. In civil engineering applications with structural and non-structural purposes, steel fibers are the most used fiber type because of its high technical properties and ductility. Steel fibers in concrete provide improved ductility by blocking or delaying the onset of cracks, crack opening and crack propagation. Thus, SFRC shows superior performance than traditional concrete in mechanical properties especially tensile strength and toughness [3–5]. With these superior properties, SFRC finds a wide application area in the structural elements subjected to dynamic loads or tensile, shear and bending. In addition, SFRC is preferred for prefabricated buildings such as prestressed beams, sewage pipes, tunnel segments and pile foundation elements [6–9].

Nowadays, researchers know almost every aspect about the SFRC. It is not known what the effective solution is for a practical mix design of SFRC. The mixture design of concrete can be defined as the process of detecting suitable proportions and amounts of concrete content with aimed fresh and hardened properties. The most commonly aimed properties of concrete in mix design are workability and compressive strength [10,11]. The most well-known approach to the mix design of SFRC is adding steel fibers as the reinforcement into the traditional concrete. Often, in this case, the compressive strength is taken into consideration as the

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only mechanical performance criterion. In addition to this design process, fiber content is calculated according to the SFRC standards or the studies in the literature. These standards and studies in the civil engineering literature give some rules and suggestions for the mix design of SFRC regarding workability and mechanical properties as distinct from traditional concrete design criterions [1,3–5,12]. But, these may cause difficulties in finding the aimed properties and may lead to an increase in the number of trial mixtures in the production process [13].

Many experimental and analytical studies about SFRC in the literature have been focused on mixture proportions, type of concrete, curing age, fiber geometry, fiber aspect ratio and fiber volume fraction (V_f), etc [13–16]. The results of these studies show that tensile strength and toughness are the most important mechanical properties of SFRC, but that the compressive strength does not change much [13–16]. Thus, it is obvious that mix design of SFRC needs other mechanical criteria. Yalçın [17] and Yalçın et al. [18] investigated performance-based design with respect to performance classes of flexural tensile strength in addition to performance classes of compressive strength for the mix design of SFRC. Divorkin et al. [12] also considered this mix design problem and emphasized that the concrete ingredients ratios and their interactions with each other were neglected for the mix design of SFRC in the literature. This negligence reduces the accuracy and efficiency of the design. Moreover, Dvorkin et al. [12] worked on an optimum SFRC mix design and proposed some design formulations with five parameters such as the amount of steel fiber, water-to-cement ratio, fineness modulus of fine aggregate, workability and sand-to-cement ratio. Finally, a highly useful and practical design nomogram was presented which predicts fiber content and water-to-cement ratio for a given workability class and flexural strength value [12]. Figueiredo et al. [19] underlined that the toughness properties have to be included the design of SFRC. They executed a correlation between steel fiber properties and the toughness. Moreover, they produced a mix design utilized Abrams' Law [20].

Several useful suggestions were made for the mix design of SFRC used in special structures considering the properties like workability and volume of voids, etc. [21–24]. But these suggestions cannot be valid for some application areas. One of the most outstanding approaches is to formulate the design parameters using statistical methods. Bayramov et al. [25] and Koksal et al. [26] produced such formulas giving the fracture energy of SFRC to minimize the brittleness for the optimum mix design. Koksal et al. [27] carried out an optimum design of SFRC plate specimens with optimum fiber aspect ratio and amount. To make the toughness maximum and keep the cost minimum, only two different concrete strength classes were considered. Huo et al. [28], Zhao et al. [29] and Huo et al. [30] developed a method called binary superposition mix design method and analyzed the effects of V_f and the thickness of the cement matrix bonded the steel fibers on the compressive, splitting tensile and flexural strengths of SFRC. As a result, increasing V_f affected positively the toughness of SFRC. They also worked on technical formulations for SFRC structural elements considering the flexural strength. To eliminate the cost, and time-consuming tensile tests in the production process of SFRC, Behnood et al. [31] built machine learning models, which predicted splitting tensile strength from compressive strength of SFRC. For the mix design of SFRC, formulations or models can be used accurately, but they cannot provide a practical design. Moreover, each formula optimizes one parameter at a time. To optimize the ingredients of SFRC and their proportions, and to determine the interactions between them may require so many formulas while providing aimed workability and mechanical properties of SFRC. There are also numerous experimental and numerical studies about the special types of SFRC such as self-compacting, high performance, etc. [32–36]. But it is obvious that these models or formulations can be just used for the type of SFRC of which it belongs to. For instance, a design method proposed for the self-compacting SFRC which has high workability cannot be used for normal SFRC [37].

For the SFRC, which is well-known for its high tensile performance and toughness, it is hard to find a practical mix design method comprising workability and mechanical properties simultaneously as emphasized in the studies of Dvorkin et al. [12], Ferrara et al. [32] and Lin et al. [33]. Hence, the purpose of this study is to test experimentally the concept of preliminary mix design of SFRC and to serve up an efficient solution for this matter. Because considering the SFRC as a costly type of concrete due to steel fibers, selecting the right mixture sometimes increases the number of trial mixtures as mentioned before. It also becomes a problem given the loss of time and labor. Therefore, a practical mix design is required for selecting the optimum amount of the ingredients and the mechanical properties of SFRC. As a result, the effective solution developed in this study could be a supplementary contribution to the mix design problem of SFRC literature. This method provides the users both an economic production process and practically detecting aimed fresh properties and mechanical properties including splitting tensile and flexural strengths and also toughness.

2. Experimental studies

2.1. Materials and mixing procedure

CEM I 42.5 N type Portland Cement was used for all the mixtures, which complies with the requirements of the European Standards TS EN 197-1 [38]. The chemical composition and mechanical properties of the cement were given in Table 1. Crushed calcareous aggregates which have maximum aggregate size of 16 mm were used in all mixtures. The specific gravities of coarse (16 ~ 8 mm), medium (8 ~ 2 mm) and fine (1 mm ~ filler) aggregates were respectively 2.68, 2.60 and 2.58 g/cm^3 and the water absorption rate of aggregates were also respectively 0.3, 2.2 and 3%. To provide good workability for the fresh SFRC, a polycarboxylate-based super plasticizer (SP) which has the specific gravity of 1.1 g/cm^3 admixture was used.

The hooked end steel fibers used in the SFRC mixtures were made of drawn low-carbon steel. Properties of steel fibers used in this study were given in Table 2. As seen in Table 2, two types of steel fiber were used in this study with the codes 40/30 and 80/60. Thus, it would be possible to obtain a mix design for different steel fiber types, as well.

In the production process, drum type concrete mixer with 250 L capacity was used for casting SFRC mixes (Fig. 1). First, the dry materials (fine and coarse aggregates and also cement) were mixed together during one minute. After mixing these dry materials homogeneously, mixture of water and SP were added, and all were mixed completely for two minutes. Finally, steel fibers were added to the mixer slowly and in clump-free state to not cause any clustering by the mixer blades according to recommended by ACI 544 standards [5,6]. Total mixing time from beginning to end for SFRC was five minutes.

The cube and beam molds were filled at once, and settlements of the mixtures have been achieved by using external vibration. During all these operations, the temperature and relative humidity in the laboratory were 28 ± 3 °C and 50 ± 2%, respectively.

Table 1
Properties of cement.

Chemical Properties	%	Mechanical Properties		
CaO	63.2	Compressive strength	2 days	22.4
SiO_2	20.1	(N/mm^2)	7 days	39.4
Fe_2O_3	4.15		28 days	51
Al_2O_3	5.88	Physical Properties		
SO_3	2.61	Initial setting time (min)	161	
MgO	2.03	Final setting time (min)	260	
Cl	0.007	Total volume exp. (mm)	0.4	
Loss of ignition	1.7	Specific surface (cm^2/g)	3749	
Insoluble residue	0.3	Specific gravity	3.1	