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Development of an optimum mix design method for self-compacting concrete based on experimental results

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HIGHLIGHTS

- An optimum mix design method has been developed for SCC.
- The optimum mix resulting from the proposed method is more suitable than Taguchi method.

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ABSTRACT

The main objective of this study is to develop an optimum mix design method for self-compacting concrete (SCC) based on experimental results. For this purpose, mix design of self-compacting concrete is formulated as an optimization problem. Given the importance of manufacturing costs of concrete, the total cost of one cubic meter of self-compacting concrete is considered as the objective function in the optimization problem, which must be minimized. Limitation of the 28-day compressive strength and slump flow of self-compacting concrete are considered as the main inequality constraints. To ensure that sum of concrete components makes unit volume, an equality constraint is considered. To formulate the self-compacting concrete mix design optimization problem based on experimental data, forty-two different mix designs of self-compacting concrete are presented and three cylinder specimens are made and tested for each of them. Two mathematical models are developed to estimate the strength and the slump of the concrete and used to define the main constraints in the mix design optimization model. The concrete specimens are prepared in a construction site in Sanandaj in Iran. Considering importance of sand grading on the compressive strength of self-compacting concrete, stone powder is used to improve sand fineness modulus. The sequential quadratic programming is employed to solve the optimal mix design problem of self-compacting concrete based on proposed model. In order to verify the proposed method, the mix design problem is solved for several case studies and then the final optimal mix designs are made in laboratory and mechanical properties of specimens are evaluated. The results show that the proposed method satisfies the mechanical characteristics of the self-compacting concrete, besides minimizing the cost of the concrete and automating the mix design process.

1. Introduction

Self-compacting concrete is a concrete mixture that flows under its own weight and does not require any external vibration for compaction. Many researchers around the world are looking for finding the appropriate mix design for self-compacting concrete as well as its mechanical properties and durability. In making this concrete, the increased use of cement usually leads to high production costs that is unfavorable. Costs of materials used in concrete structures are not the same and their amount must be optimized based on requirements of each structure. Application of some admixtures aims to reduce cement consumption. This aim can be effectively obtained by choosing the appropriate aggregation and optimizing the mix without adding additives. Achieving self-compacting concrete mix design with minimum cost is very important for consumers. The cost of materials such as concrete is an important factor affecting the cost of construction of concrete structures and can be one of the main reasons for the development and popularity of special concrete. The first serious work in this area was conducted by Simon et al. [1]. These researchers con-

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ducted an experiment by statistical mixing for high-performance concrete mix design. They used quadratic polynomials to find the relation between compressive strength and design variables. Ashby used a multi-objective optimization method to meet given design requirements for selection of a material [2]. In his study, it was found that trade-off surfaces give a way of visualizing the alternative compromises, and utility functions identify the part of the surface on which optimal solutions lie. Karihaloo and Lange-Kornbak employed rigorous mathematical programming techniques for design of fiber-reinforced concrete mixes to have both high tensile strength and high ductility [3]. Microstructural-macroscopic relationships were used to formulate the corresponding optimization problem. Ghezal and Khayat optimized self-compacting concrete with stone powder using statistical factorial design [4]. In their study, to reduce the cost of concrete, stone powder was used as a filler material. They employed response surface methods to optimize a four component concrete containing limestone filler subject to eight performance criteria. Muthukumar and Mohan optimized mix proportions of polymer concrete to have minimum void [5]. For each polymer concrete combination, the mechanical properties were studied. Each mechanical property was individually optimized for maximum values and compared with the experimental data. Yeh presented a computer-aided design method for determining optimum concrete mixtures [6]. The strength and slump was modeled using a modeling module based on neural networks. In his study, it was found that the modeling module can generate rather accurate models for compressive strength and slump for concrete and the optimization module can generate the lowest cost mixtures. Ozbay et al. were analyzed mix proportion parameters of high strength self-compacting concrete by using the Taguchi's experiment design methodology for optimal design [7]. In their study, the best possible levels for mix proportions were determined for maximization of ultrasonic pulse velocity, compressive strength, splitting tensile strength and for the minimization of air content, water permeability, and water absorption values. Lian and Zhuge investigated effects of various mix designs on the compressive strength and permeability of permeable concrete [8]. The optimum aggregate and mix components design were consequently recommended for enhanced permeable concrete. Soto-Pérez et al. applied response surface methodology to optimize the cement paste mix design with fly ash and nano-iron oxide as admixtures [9]. They found the optimum ratios of water-to-binder, fly ash-to-binder and nano-iron oxide-to-binder. Moini et al. were considered aggregate packing to optimize concrete mixtures by establishing the correlation of compressive strength and aggregate packing [10]. They used power curves and coarseness chart for aggregate optimization. Lindquist et al. implemented of a step-by-step concrete mixture design procedure to determine an optimized aggregate gradation [11]. The design process was iterative and was dependent on the gradations of available aggregates, the cementitious material content of the concrete mixture, and the maximum aggregate size. The main objective of this study is to develop a method for optimizing self-compacting concrete mix design. For this purpose, first, the self-compacting concrete mix design optimization problem is formulated based on experimental results stablishing mathematical models for slump flow and compressive strength of the concrete. Then the problem is solved by sequential quadratic programming. The ability and efficiency of the proposed method are demonstrated by testing real-life concrete mixes.

2. Experimental study

In this study, experimental data are produced to develop the model for optimal self-compacting concrete mix design. In this section, properties of materials used in the study, mixing the aggregates, self-compacting concrete mix designs, concrete specimens and test results are studied.

2.1. Properties of materials

Materials used in this study included a type I Portland cement, tap water, gravel, sand, stone powder, and a polycarboxylate-based superplasticizer (Type RM of Abadgaran Company). Detailed characteristics of cement have been listed in Table 1. The coarse aggregate was a gravel with a maximum aggregate size of 19 mm and a bulk density of 2.84. River sand had a bulk density of 2.75 and a sand equivalent of 75. The stone powder was used to modify properties of the sand. Super plasticizer was used to obtain the self-compacting concrete characters at fresh state. The specific weight of superplasticizer was 1.12 g/cm^3. The amount of the super plasticizer has been ranged from 0.3% to 0.9% by weight of cement in accordance with the manufacturer's recommendations. The grading of the aggregates and the powder are given in Table 2.

2.2. Concrete mix designs

The mix composition shall satisfy all performance criteria for the concrete in both the fresh and hardened states. Generally, it is advisable to design conservatively to ensure that the concrete is capable of maintaining its specified fresh properties despite anticipated variations in raw material quality. In the present study, in the first step, several initial mix compositions were prepared and laboratory trials were used to verify their properties. Then adjustments to the initial mix compositions were made and 42 main self-compacting concrete mix designs, shown in Table 3, were prepared and tested. All concrete mixes were designed based on the ENFARC [12]. Mix design selection and adjustment can be made according to the procedure shown in Fig. 1.

2.3. Concrete specimens

Forty-two different mix designs were considered in this study and three cubic specimens of $150 \times 150 \times 150$ mm were made for each of them. Accordingly, one hundred twenty-six specimens were casted in the laboratory. All concrete mixes were prepared in a pan mixer. The batching sequence consisted of mixing the dry ingredients for one minute, then adding the water with super plasticizer and mixing the concrete for another four minutes. The specimens were demolded after 24 h and then kept in lime-saturated water at a temperature of 25 °C for 28 days.

2.4. Test results

Since compressive strength of the concrete is very important to determine a mix design and some of the mechanical characteristics such as tensile strength and Young's modulus are dependent on it, in this study, compressive strength is considered as the main parameter to control the mix design. Slump test is a meaningful indication for showing the flow range of self-compacting concrete. There are some other methods such as U box and V box for measuring the flow of SCC but the slump is more reliable. Therefore, the slump test is selected to be used for testing the flow of self-compacting concrete. In the present study, compressive strength and slum flow of the self-compacting concrete mixes are investigated to determine the optimum proportion of SCC. Two experimental tests including the compressive strength and slump tests are performed on all the specimens. To obtain the compressive strength for each mix design, three cubic specimens of $150 \times 150 \times 150$ mm are tested and the average of their compressive strengths is considered as the final compressive strength of the