Factorial design models for proportioning self-consolidating concrete

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Paper received: September 29, 1998; Paper accepted: April 19, 1999

ABSTRACT

A factorial design was carried out to model the influence of key mixture parameters on properties affecting the performance of self-consolidating concrete (SCC). Such responses included slump flow and rheological parameters, filling capacity and V-funnel flow to assess restrained deformability, surface settlement to evaluate stability after casting, and compressive strength. Thirty two mixtures were prepared to derive the statistical models and nine others to evaluate their accuracy. The models are valid for a wide range of mixture proportioning. The paper presents the derived models that unable the identification of underlying primary factors and their interactions that influence the modelled responses of interest for self-consolidating concrete. Such parameters can be useful to reduce the test protocol needed for the proportioning of self-consolidating concrete. The usefulness of the models to better understand trade-offs between mixture parameters and compare the responses obtained from various test methods are highlighted.

1. INTRODUCTION

Self-consolidating concrete (SCC) is a highly flowable concrete that can spread easily through restricted sections under its own weight without segregation and blockage. Such concrete is used to ensure the filling of congested sections and areas with restricted access to vibration. It is also employed to improve the productivity of concrete placement and site working conditions resulting from noise reduction due to the elimination of vibration consolidation.

The proportioning of SCC is complicated because of the various contradictory requirements needed to ensure excellent flow characteristics and proper mechanical properties. For example, a highly flowable SCC should have a relatively low yield value to ensure good deformability but an adequate resistance to segregation and bleeding until the onset of hardening. An increase in water-to-cementitious materials ratio (w/cm) can secure high deformability, however, it can reduce the cohesiveness and cause segregation of aggregate that can lead to blockage of the flow. Inter-particle friction between coarse aggregate, sand, and fines increases the internal resistance to flow, hence limiting the deformability and speed of flow of the fresh concrete. Such friction is especially high when the concrete flows through a restricted spacing because of the greater collision between the various solids that increase viscosity. A local increase in aggregate density in a poorly viscous system can lead to coagulation and arching of the aggregate and

RéSUMÉ

Pour la formulation du béton autoplantant (BAP) plusieurs gâchées s'imposent, étant donné qu'il faut maîtriser tous les facteurs affectant les propriétés à l'état frais et durci du béton. Des modèles statistiques ont été générés à partir de la réalisation d'un plan d'expérience. Ces modèles identifient les paramètres importants de la formulation sur la performance du béton autoplantant : la déformabilité caractérisée par l'essai de l'étalage, les paramètres rhéologiques, la capacité de remplissage, et l'entonnoir; la stabilité traduite par le test du tassement et la résistance à la compression. La modélisation a nécessité un total de 32 gâchées de béton. Neuf autres mélanges ont été ajoutés afin de vérifier la validation des modèles établis. Ce papier présente les modèles générés qui traduisent l'effet des paramètres principaux ainsi que leur interactions sur les réponses mesurées. L'utilité des modèles à établir une meilleure compréhension entre les paramètres des mélanges et de trouver des corrélations entre les différents tests réalisés est discutée.
an interference with the deformability of the concrete in a restricted area [1-4]. Inter-particle friction between cement grains can be reduced by using a high-range water reducer (HRWR) to disperse the cement grains. A high dosage of HRWR can however lead to segregation and blockage of the flow. The combined use of HRWR and viscosity-enhancing agent (VEA) or a HRWR and a low w/cm can reduce the free water content necessary to ensure adequate viscosity and maintain good suspension of coarse aggregate and reduce inter-particle collision and coagulation of solid particles during the flow.

In addition to providing adequate stability during placement, the concrete should have a proper stability in the formwork until hardening to minimize bleeding and segregation. This is important to secure homogeneous properties of the hardened concrete. Ensuring adequate stability is critical in deep sections where highly flowable concrete can exhibit segregation and bleeding and a non-uniform distribution of mechanical properties, bond to reinforcing steel, and microstructure [5-7].

The contradicting workability requirements needed for successful placement of SCC necessitate tailoring a concrete mixture to ensure good balance between deformability and stability to prevent blockage during the flow and ensure a homogeneous suspension of the concrete constituents. Such homogeneous distribution is necessary to ensure adequate structural performance and durability. Engineers are faced with the complex task of manipulating several variables to enhance concrete performance and reduce cost. Some guidelines exist for mixture proportioning of SCC to reduce the extent of trial mixtures required to strike a balance between the various contradicting mixture requirements. The recommendations are mainly based on increasing the paste volume, reducing the coarse aggregate volume and sand to powder ratio, optimizing the granular squelette of all solids, etc. For the most part they treat a specific class of concrete and may require special test equipment or software [8-11]. The majority of mix design guidelines do not consider the specific effect of mixture parameters and their interactions on concrete performance. The objective of this paper is to illustrate the feasibility of using a statistical experimental design approach to identify the relative significance of primary mixture parameters and their coupled effects on relevant properties of SCC. The models can be used to evaluate the potential influence of adjusting mixture variables on concrete properties required to ensure successful development of SCC. Such simulation can help identify potential mixtures with a given set of performance criteria that can be tried in the laboratory, hence simplifying the test protocol needed to optimize SCC.

2. FACTORIAL DESIGN APPROACH

Five key mixture parameters that can have significant influence on mixture characteristics of SCC were selected to derive mathematical models for evaluating relevant properties of SCC. The five variables included the concentrations of VEA and HRWR, the w/cm, the content of cementitious materials (CM), and the volume of coarse aggregate (Vca). The concrete responses that were modelled were the slump flow, and rheological parameters to evaluate the deformability of concrete in a non-restrained area, as well as the filling capacity and V-funnel flow time to evaluate the deformability in a restrained area that reflect its deformability and resistance to blocking. The other modelled responses included the surface settlement, segregation resistance, and compressive strength (fc) after 7 and 28 days.

The underlying factors that influence fresh concrete properties and strength development are too complicated to permit the development of an exact mathematical model. Therefore, an empirical statistical model was derived over a wide working range of mixture proportioning. A 2⁵⁻¹ statistical experimental design was used to evaluate the influence of two different levels for each of the five mixture variables on the relevant concrete properties. Such a two-level factorial design requires a minimum number of tests for each variable. The initial levels of the five selected mixture variables were carefully chosen after reviewing the demand constraints imposed by the targeted concrete properties. Given the fact that the expected responses do not vary in a linear manner with the selected variables and to enable the quantification of the prediction of the responses, a central composite plan was selected where the response can be modelled in a quadratic manner. Such a plan enables the evaluation of the five selected mixture parameters with each studied in five distinguished levels: codified values of α, -1, 0, 1, and α. The α value is chosen so that the variance of the response predicted by the model would depend only on the distance from the center of the modelled region. The value α is equal to \( N_F^{1/4} \) where \( N_F \) is the number of fractional factorial points \( 2^{5-1} \times 1 = 16 \) \( (\alpha = 16^{1/4} = 2) \).

The 32 mixture combinations used in the factorial design consisted first of 16 mixtures for the fractional factorial plan where the mixtures were set at coded values of -1 and +1. The 2⁵⁻¹ fractional factorial design was expanded to include 10 additional mixtures where each variable was adjusted separately at the extreme α value of -2 and +2 with the other variables maintained at the 0 central points. This was done to consider extreme values of the five principal variables on the measured responses. Six replicate central points were prepared to estimate the degree of experimental error for the modelled responses. The coded variables are calculated as follows:

- coded w/cm = (absolute w/cm - 0.435) / 0.0325
- coded CM = (absolute CM - 480) / 60
- coded VEA = (absolute VEA - 0.125) / 0.0375
- coded HRWR = (absolute HRWR - 0.7) / 0.2
- coded Vca = (absolute Vca - 320) / 40

The experimental region modelled in this study is illustrated in Table 1. Although the models are valid for mixtures between the -2 and +2 regions, it is recommended to limit their use to the area bound by coded values corresponding to -1.5 to +1.5. This can eliminate the outer regions approaching the edges of the modeled