Construction and Building Materials 161 (2018) 246–253

Contents lists available at ScienceDirect

Construction and Building Materials

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

Norm method to define and evaluate robustness of self-compacting concrete due to component quantity variations

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HIGHLIGHTS

- The variations of water and aggregate contents strongly affect the fresh properties of SCC.
- The robustness of the hardened properties of SCC is higher than the fresh-related properties.
- The norm method can evaluate the robustness of SCC in a more intuitive way.
- Decent consistency can be found between the norm method and previous evaluation method.

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 24 October 2017
Accepted 26 November 2017

Keywords:
Robustness
Self-compacting concrete
Low-binder
Norm
Workability

ABSTRACT

Presently, self-compacting concrete (SCC) has been widely used and has many incomparable advantages compared to the traditional vibrated concrete. While it also has many disadvantages among which the robustness of SCC seems to be a serious problem at the production stage. In this study, both the fresh and hardened properties of a low binder content SCC were studied in the cases of the quantity variations of components. Meanwhile, a new robustness assessment method based on the concepts of linear algebra (using norm analysis of vectors) was proposed in order to define and evaluate the robustness of SCC. The results show that the robustness of the hardened properties is higher than that of the fresh-related properties. Additionally, by adopting the proposed method, the robustness of the SCC mixtures can be described and evaluated in a more intuitive way and both the variations of moisture content and aggregate quantities, such as the volume fraction and the gradation, strongly affect the fresh properties of the low-binder SCC. Finally, a good consistency was found between the proposed method and a previous robustness evaluation method thus proving that the proposed methods can be regarded as a concise and effective tool to define and evaluate the robustness of the SCC mixtures.

1. Introduction

According to the European Guidelines for SCC, the robustness of concrete is defined as "*the capacity of concrete to retain its fresh properties when small variations in the properties or quantities of the constituent materials occur*" [1], which means the term robustness is not a specific property but a comprehensive reflection of the properties of SCC in the cases of different kinds of fluctuations of the component quantities. Robustness, defined here as the sensitivity of the mix to the variations in the quantity of the components, seems therefore to be the most critical matter of contention in developing a successful SCC technology.

However, the definition of robustness is a qualitative concept and the understanding of it still remains to be studied. Researchers have done a lot of work on the influence mechanism and extent of different factor variations on the properties of SCC while others focus on establishment of the evaluation methods to describe the robustness of SCC [2–9].

Billberg et al. [2,3] have studied the influence of moisture, fine aggregate and temperature variations on the rheological properties and concluded that the moisture content variation impacts the yield stress and the viscosity of SCC to a much higher extent than that of the other two factors. Meanwhile, they introduced the concept of Robustness Area in a rheograph to reflect the impacts of different factors variation. Nevertheless, the idea of comparing the

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https://doi.org/10.1016/j.conbuildmat.2017.11.143
0950-0618/© 2017 Published by Elsevier Ltd.

size of the area in a rheograph may not represent real workability in engineering practice, and some mixtures with rheological parameters within the recommended area in the rheograph may have poor workability [4].

Nunes et al. [5] adopted a methodology of factorial design to study the robustness of SCC based on 5 factors that determine the SCC mix proportion (i.e. water to powder volume ratio, filler to cement weight ratio, superplasticizer to powder weight ratio, sand to mortar volume and solid volume, etc. [5]) as well as the practical variations of the SCC components observed in a precast factory. The method provides comprehensive results of the influences and interactions of the variations of each factor on the SCC fresh properties but also proved to be complex and laborious for the engineering practice. Naji et al. [6] adopted a statistical approach to estimate the robustness of SCC with the additions of different types of viscosity modified agents under ±1% variations of the sand humidity with both fresh and hardened performances of the SCC mixtures tested. Although the statistical method is a scientific means of describing the robustness of SCC, these results always lack of physical meaning and need to be further improved.

In addition, some studies have paid closer attention to the establishment of the Robustness Index in order to quantitatively evaluate the robustness of SCC [7–9]. Gálvez-Moreno et al. [7] adopted the concept of the confidence interval for a reference SCC mix to obtain the tolerance range of different workability tests within a series of component quantity variations through the intersection of the performance variation curve and the confidence interval boundaries. The Robustness Index is then obtained by summing the tolerance ranges of different measured properties. This evaluation method provides a general understanding of the influence degree for each component quantity variation within various measured properties. Other researchers also established the Robustness Index by calculating the length of a fitting curve of several fluctuating results in a rheograph [8] or by adopting the logarithms of the maximum and minimum values of calculated rheological parameters [9].

It seems that all the above studies have provided useful guidance for evaluating the robustness of SCC. Nevertheless, some of them lack enough information to characterize the robustness of SCC namely the main indexes of fresh SCC such as the flowability, the passingability as well as the stability etc., which need to be all taken into consideration in analyzing the robustness of SCC. Therefore, in order to describe the concept of robustness in a more quantitative way, the term should contain numerous factors in order to make it available for both engineering and research.

This study aims to investigate the influence of different component quantity variations on both the fresh and hardened properties of SCC with low binder content and establish a new and comprehensive method to evaluate the robustness of SCC. Accordingly, one type of low binder content SCC is experimentally analyzed and some of the experimental results from the literature are also used in order to analyze and validate the robustness evaluation method proposed in this paper.

2. Expression and evaluation of robustness

Assuming that the vector $\boldsymbol{R_{comp}} \in \boldsymbol{R^n}$ stands for the robustness vector of various properties of SCC mixtures (slump flow, V-funnel flow time, strength, shrinkage etc.), in the case of one specific component quantity variation (superplasticizer (SP), water, aggregate, etc.), then $\boldsymbol{R_{comp}}$ can be written as:

$$\boldsymbol{R_{comp}} = (R_{t_1}, R_{t_2}, \dots, R_{t_n}) \quad (1)$$

where $t_i(i = 1, 2, \dots, n)$ means the specific measured property of SCC mixture.

$$R_{t_i} = \frac{\eta \sum_{j=1}^{m} |\Delta V_{t_{i\_j}}|}{m * p} \quad (2)$$

where m is the number of test groups of one specific component; $\Delta V_{t_{i\_j}}$ is the fluctuation degree of the measured property of t_i which is calculated by the difference between the results of the variation mixture and the reference mixture (the calculation details are shown in Section 5.1); p is the percentage of the component quantity variation; η is the coefficient of importance which is considered as equal ($\eta = 1$) for the measured property of t_i since the SCC mixture studied here is not designed for any specific application. Hence, the vector $\boldsymbol{R_{comp}}$ consists of a series of non-negative numbers, namely $R_{t_i}(i = 1, 2, \dots, n)$. It is easy to calculate the percentage of the variation range once the quantity variation of each component in the construction process is known.

Furthermore, assuming that the matrix $A_{c\_t} \in R^{m \times n}$ stands for the robustness matrix to the various measured properties of SCC mixtures for the various component quantity variations then A_{c_t} can be expressed as follows:

$$\boldsymbol{A_{c\_t}} = (\boldsymbol{R_{c_1}}, \boldsymbol{R_{c_2}}, \dots, \boldsymbol{R_{c_m}})^T \quad (3)$$

where $c_j = (1, 2, \dots m)$ are the different components and $\boldsymbol{R_{c_1}}, \boldsymbol{R_{c_2}}, \dots, \boldsymbol{R_{c_m}}$ are the robustness vectors of the different component quantity variations.

According to the concept of the matrix norm (see Appendix) as well as the definition of the vector $\boldsymbol{R_{comp}}$, it is reasonable to evaluate the robustness of SCC by calculating the 1-Norm and 2-Norm of $\boldsymbol{R_{comp}}$:

$$||\boldsymbol{R_{comp}}||_1 = \sum_{1}^{n} |R_{ti}| \quad (4)$$

$$||\boldsymbol{R_{comp}}||_2 = \left(\sum_{1}^{n} |R_{ti}|^2 \right)^{1/2} \quad (5)$$

where and $||\boldsymbol{R_{comp}}||_1$ and $||\boldsymbol{R_{comp}}||_2$ indicate the total effect and the average effect of the measured properties on the robustness of SCC for one specific component quantity variation.

Furthermore, it is of great importance to know which properties are more sensitive than the others when the fluctuations of different component quantities occur. Assuming that the vector $\boldsymbol{R_{test}} \in \boldsymbol{R^m}$ stands for the robustness vector to the various component quantity variations of SCC mixtures for one specific measured property then $\boldsymbol{R_{test}}$ can be written as follows:

$$\boldsymbol{R_{test}} = (R_{c_1}, R_{c_2}, \dots, R_{c_m}) \quad (6)$$

where $c_j = (1, 2, \dots m)$ means the different quantity variations of each component.

Then in a similar fashion $||\boldsymbol{R_{test}}||_1$ and $||\boldsymbol{R_{test}}||_2$ indicate the total effect and the average effect of the component quantity variations on the robustness of SCC in the condition of one specific measured property, respectively.

3. Materials and test methods

3.1. Powder materials

Portland cement with strength grade of 52.5 MPa obtained from Xiao Yetian Cement Co., Ltd. (Jiangsu, China) was used. The apparent density of cement is 3060 kg/m^3, and the chemical and mineral compositions are listed in Table 1. Two types of ground limestone powder (LP_1 and LP_2) with different particle size distributions (PSD) were used as powder materials. The densities both are 2650 kg/m^3. The PSD of these three types of powders tested by a HELOS-SUCELL Laser Particle Size Analyzer are shown in Fig. 1.