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Image analysis applications on assessing static stability and flowability of self-consolidating concrete

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ABSTRACT

A digital image processing (DIP) method associated with a MATLAB algorithm is used to evaluate cross sectional images of self-consolidating concrete (SCC). Two new parameters, such as inter-particle spacing of coarse aggregate and average mortar-to-coarse aggregate ratio, defined as average mortar thickness index (MTI), were proposed to quantitatively evaluate the static stability of SCC. Statistical models were developed to predict flowability of SCC mixtures. Test results revealed that the proposed DIP method and MATLAB algorithm can be successfully used to derive inter-particle spacing and MTI and quantitatively evaluate the static stability on hardened SCC samples. A probability density of 60% from histogram analysis appears to be a reasonable threshold for indicating a uniformly distributed SCC mixture. For a given mortar yield stress, a critical mortar viscosity of 1.30 Pa s tends to significantly affect the trend of slump flow changing with MTI. The investigated relationship between parameters measured from DIP method and existing theoretical frames is well correlated. The outcome of this study can be of practical value for providing an efficient and useful tool in designing mixture proportions of SCC.

1. Introduction

Aggregate as a primary component occupies up to 80% of concrete volume. It can thus exert a large influence on concrete performance [1]. Aggregate characteristics, such as size, distribution, and shape, are key parameters of mixture design that affect workability of concrete mixtures [2]. A well-proportioned self-consolidating concrete (SCC) mixture can be achieved by controlling the aggregate system, paste quality, and paste quantity. For a given paste quality, the lower the paste quantity, the more economical the concrete is. To achieve a minimal paste quantity for a given concrete performance, a well-graded aggregate system is demanded because the dense packing of aggregate particles results in less voids for paste to fill in [3]. Thus, additional paste in a designed concrete mixture can function as a lubricant layer to coat the surfaces of aggregate particles and make the mixture have desirable workability. The thickness of this paste layer is referred as excess paste thickness. Achieving the designed aggregate distribution and proper excess paste thickness is critical to control certain engineering properties and structure performance of concrete [1].

In this study, digital image process and analysis (DIP) method is used to evaluate the static stability and to develop statistical models for predicting flowability of hardened SCC mixtures designed for cast-in-place applications. The spacing between coarse aggregates particles and average mortar-to-coarse aggregate ratio, defined as average mortar thickness index (MTI), hereafter can be estimated using proposed algorithm in DIP method (as illustrated in Fig. 2). MTI is then used to build statistical models associated with mortar rheology parameters to predict flowability of SCC mixtures. The following flow chart illustrates the main structure of this research (Fig. 1).

2. Background

2.1. Excess paste theory and Paste-to-voids volume ratio concept

Previous researchers have investigated the effects of aggregate distribution and paste quantity on the properties of conventional concrete (CC) and SCC mixtures using: (1) excess paste/mortar theory [4,5]; (2) paste-to-aggregate void volume ratio concept [6–8].

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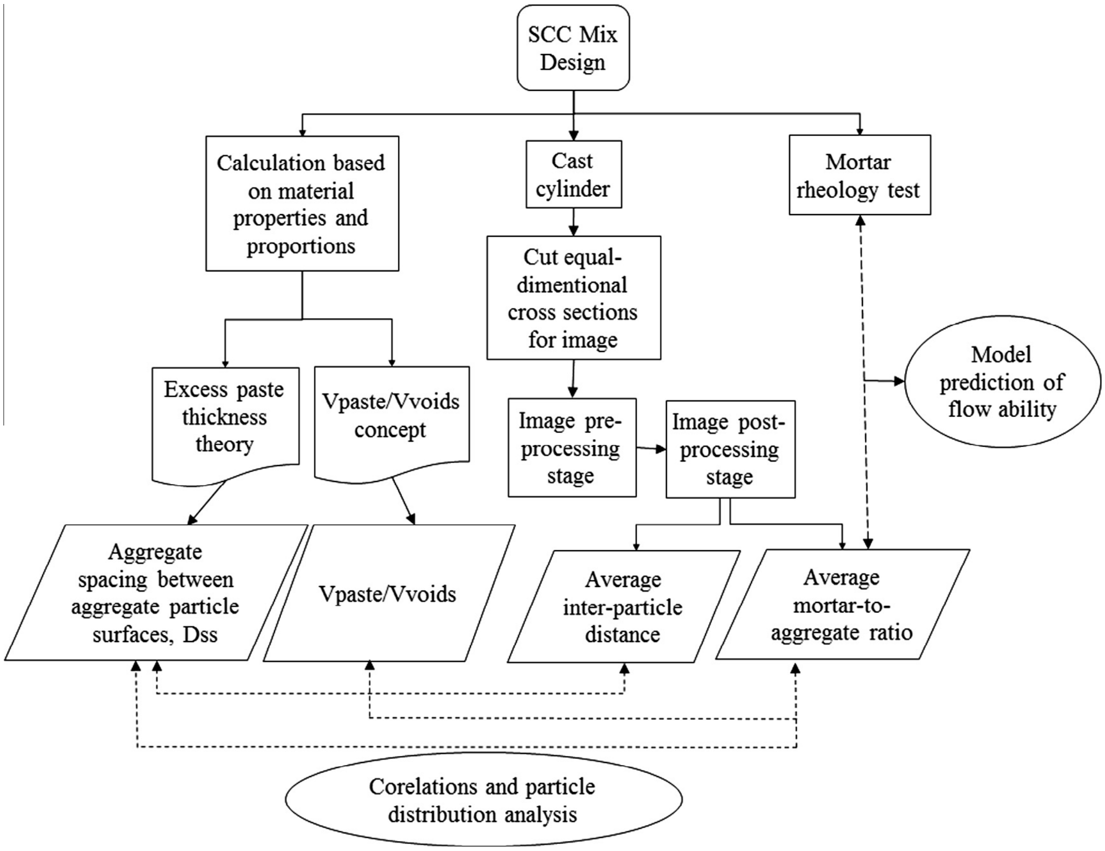

Fig. 1. Research plan flow chart.

The "excess paste theory" was originally proposed by Kennedy [9]. The key of this theory was known as two-phase theory in which a paste phase is used to fill up the voids between the aggregate phase. A desired workability can be achieved by the use of sufficient paste volume to fill the voids so as to control frictions between aggregate particles. The paste layer around aggregate particles needs to be thick enough to achieve a good workability and thin enough to prevent aggregate from segregating [8–10]. Hu and Wang [4] extended this theory to "excess mortar theory", in which paste and fine aggregate were considered as a whole system to provide segregation resistance and lubrication effect.

The "excess paste theory" was used to design SCC mixture proportions by Bui et al. [5]. The average spacing between aggregate particle surfaces (particles are assumed to be spherical), D_{ss}, and the average aggregate diameter, D_{av}, were estimated through Eqs. (1) and (2). These two parameters combined with paste rheology models were used to design SCC mixture proportions and predict workability. Fig. 2 shows the schematic relationship among aggregate spacing, average aggregate diameter, and aggregate system used in designing SCC mixture proportions and MTI and inter-particle spacing defined in current study [5].

$$D_{ss} = D_{av}\left(\sqrt[3]{1 + \frac{V_p - V_{void}}{V_c - V_p}} - 1\right) \quad (1)$$

where V_p = paste volume; V_{void} = volume of voids in densely compacted aggregate determined in accordance with ASTM C29 [34]; V_c = total concrete volume; and D_{av} = the average aggregate diameter, which is given by

$$D_{av} = \frac{\sum d_i m_i}{\sum m_i} \quad (2)$$

where d_i = average size of aggregate fraction i; and m_i = percentage of aggregate mass retained between upper and lower sieve sizes in fraction i.

An alternative concept, based on the paste-to-voids volume ratio (V_{paste}/V_{voids}), was applied to pavement mixtures by Yurdakul et al. [7] and SCC mixtures by Wang et al. [6] in accordance with Koehler and Fowler's [8] idea of relating performance of a mixture to paste volume for a given aggregate system. The concept aims at providing a quantitative method to consider the interaction between aggregate system and paste in a mixture while still meeting project requirements. It is believed to be more practical than parameters of "cementitious content" or "paste content" due to the differences between aggregate systems [7].

V_{paste}/V_{voids} can be derived by the ratio of the paste volume and the volume of voids in the combined aggregate system determined in accordance with ASTM C29 [34]. The paste volume comprises the volume of water, the cementitious materials, and measured air in the system. If all paste is used up in filling of voids between the aggregates, the ratio of V_{paste}/V_{voids} is 100%.

2.2. Digital image processing

Although calculations have been developed to assess excess paste thickness, the limitations of the calculations include:

- For excess paste theory, aggregate particles are assumed to be spherical, which is never the case in practice.
- For excess paste theory, aggregate particles are considered to be packed in a cubic lattice.
- For both theories, the segregation phenomenon of CC and SCC mixtures, when experiencing excess vibration or poor paste quality, may result in different performance between the actual