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A method for real-time moisture estimation based on self-compacting concrete workability detected during the mixing process

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HIGHLIGHTS

- A new method for real-time estimating the overall moisture of an SCC mixture was proposed.
- Fundamental derivation to estimate moisture was confirmed by verification experiments.
- Moisture contents are estimated with estimated SF values using image recognition.
- Proposed method provides convenient implementation without the need for additional measurement.

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ABSTRACT

Controlling the moisture content of self-compacting concrete (SCC) mixtures during batching is important for assuring workability and meeting design standards, but fluctuating in situ aggregate moisture contents pose a challenge. Measuring aggregate moisture before every batch is necessary, but inconvenient and expensive in hydraulic projects in China. This study developed a method for estimating the overall moisture of an SCC mixture to guide batch weight adjusting. The method includes a laboratory-based concrete test and an in situ concrete mixing process. The overall moisture estimates, determined by slump flow values, were confirmed to be reliable through verification experiments. The proposed method may serve as an alternative to manual or automated moisture measurement.

1. Introduction

Self-compacting concrete (SCC) is a highly workable material that can flow to fill gaps in reinforcements, corners of molds, and voids in rock blocks without any vibration and compaction during the placing process [1,2]. The superior workability of SCC is required to prevent compromised strength and durability in structures. Rock-filled concrete (RFC) is developed in China in 2003 as an application of SCC that can then be used for massive concrete constructions. It is indicated that RFC meets the requirements of hydraulic concrete. Due to the wide application of RFC in hydraulic projects in China, especially in small-scale projects in the countryside, the production of SCC grows significantly.

A number of different mix design approaches have been previously proposed by researchers around the world [3–9] to help ensure that mix proportions produce an SCC with proper workability. However, the same mix proportion may produce different SCC workability results in the laboratory and in situ. Characteristics of in situ batching materials (e.g., powder properties, aggregate shape, aggregate texture, aggregate moisture, the particle size distribution of the fine aggregate, etc.) may explain the workability differences [10–15]. Among these properties, aggregate moisture is most apt to fluctuate [16,17], causing both the overall moisture of the concrete mixture and the true water-powder ratio (W/P ratio) to change [18].

In typical practice, the SCC mix proportion is designed under saturated surface-dry conditions for the aggregates. In a stable concrete laboratory environment, the water absorption of aggregates can be measured just once. When performing SCC laboratory tests, the batch weights of water are adjusted by a constant amount, which is computed using the previously measured water absorption values for the aggregates. Comparatively, in situ aggregates (in stockpiles, storage bins, etc.) are rarely in steady-state conditions, especially in hydraulic projects in the China countryside. These in situ batching plants are usually built temporarily, lacking effective management of aggregate storage and equipment capable of measuring moisture content, which differ from batching stations in big cities. The aggregate is usually stored on the open yard, causing moisture contents continuously fluctuating and construction

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quality affected badly. Daily and monthly fluctuations in the surface moisture content of sands has been previously observed [19–21] and attributed to daily and monthly thermal cycles [22,23]. The surface moisture content of fine sands ranges between 4.5 and 6.5% in a given month, while the surface moisture state of sands is initially moist in the morning but shifts to a drying state in the afternoon. A similar pattern is observed for coarse sand. In addition, aggregate moisture contents are not distributed evenly in space. Aggregates located near the bottom of a stockpile are typically wetter than those near the surface of the pile.

Ideally, in situ instantaneous aggregate moisture values would be known in advance before every batch to allow batch weights to be accurately adjusted [6]. If this is not the case, the W/P ratio will be dramatically affected, as will the SCC workability [21,24], strength and durability. Note that the method of adjusting batch weights is to alter the in situ W/P ratio to the design one, which aims to achieve the desired workability as well as strength to meet the design requirements. Unlike in the laboratory, a single measure of aggregate moisture is insufficient in situ. Instead, aggregate moisture should be recorded at least once per day and perhaps more frequently when producing SCC, because this type of concrete is sensitive to changes in aggregate moisture [21]. To automate this process, some batching systems are equipped with probes that can read the moisture content of aggregates while being discharged from the hopper [25,26]. For batching systems without moisture meters or probes in country hydraulic projects, the aggregate moisture content must be measured manually, which is labor-intensive, time-consuming, and costly [27]. Automated measurement systems also have disadvantages. Moisture readings have been found to be inaccurate if the aggregate amount does not sufficiently cover the probe surface [28]. In addition, the moisture readings taken from select aggregates do not represent the overall aggregate moisture condition, which varies throughout the stockpile or storage bin and is affected by the mixing procedure [28]. Lastly, automated measurement systems using moisture meters or probes are expensive to install and maintain in situ, especially for small-scale hydraulic projects in China countryside.

In response to the challenges described above, the objective of the present study was to develop a method that enables real-time moisture determination in situ. The information that this method provides will guide SCC plant operators when adjusting batch weights.

The SCC workability is dependent not only on the moisture content of the aggregate, but also on other material characteristics, such as the particle size distribution of the fine aggregate. If the other material characteristics keep unchanged, a correlation exists between SCC workability and overall concrete mixture moisture. The difference between laboratory and in situ workability can be used to deduce the moisture difference. Real-time measurement of SCC workability is fundamental to this proposed method.

A number of real-time SCC-related analysis methods have been recently proposed, most of which rely upon image processing. Cabaret et al. [29] proposed a mixing-time analysis using image processing; mixing time is determined using a quantified color evolution in a transparent stirring tank. Daumann and Nirschl [30] used digital image processing to measure the mixing efficiency of solid mixtures comprising particles of different sizes and colors. Li [31] developed an image processing method to estimate slump flow (SF) and V-funnel (VF) values of SCC during the mixing process. Extracted images of the mixing process indicated that the action of the rotating blades in the mixer caused the fresh concrete to form two boundaries in the images, supporting prediction of SCC workability from the visual information. Thus, these findings could be used as a basis for the present research.

In summary, in this study, we developed a method for real-time estimation of the overall concrete moisture integrated with an image processing system, which utilizes fresh SCC properties throughout the mixing process. Verification experiments were performed to determine whether the proposed method was reliable. If proven reliable, the proposed method may serve as an alternative to more costly and/or time-consuming manual or automated moisture measurement methods.

2. Overview of proposed method

2.1. Correlation between SF value and W/P ratio

In SCC industry practice, engineers initially conduct several laboratory-based concrete experiments to determine proper mix proportions for production. If the aggregate contents are fixed, the mix proportion primarily considers two parameters: (1) the W/P ratio by volume (V_w/V_p) and (2) the superplasticizer (SP) dosage by volume [9,32,33]. Prior experiments have shown a strong linear correlation between the SF value of fresh concrete and the corresponding W/P ratio for a fixed SP dosage and a limited W/P ratio range [9]. Thus, the SF values could indicate the true moisture condition of a concrete mixture, considering the unique properties of fresh SCC.

For concrete batching in situ, the correlation between the SF values and W/P ratios differs because the aggregate moisture contents differ (moisture is often higher in situ than in the laboratory). The difference between the two correlations could be used to estimate the true aggregate moisture during a concrete mixing process.

Fig. 1 shows the fundamental derivation of the moisture estimating method developed in this study. It is assumed that the SF is linearly related to W/P ratio for a fixed SP dosage and a limited W/P ratio range, which is justified with Wu's experimental data [9] and preliminary trials data, as shown in Fig. 2. For a specific SP dosage and W/P ratio, the SF value of fresh SCC is easily obtained by conducting a laboratory-based concrete trial. The paired SF value and W/P ratio are marked with an *A* in Fig. 1. Because in situ aggregates are typically wetter in hydraulic projects in China, the in situ SF value will be higher for fresh SCC with exactly the same mix proportion. The corresponding paired SF value and W/P ratio are marked with a *B* in Fig. 1. A second in situ trial with a W/P ratio lower than the specific ratio is marked with a *C* in Fig. 1. Note that the horizontal coordinate of point *D* represents the true W/P ratio corresponding to the SF value at *B* and *D*. A similar relationship exists for *C* and *E*. Also note that the horizontal distance between *B* and *D* in Fig. 1 is the same as the distance between *C* and *E*, because the moisture content of the aggregates within the same batch and the powder content by volume are constant.

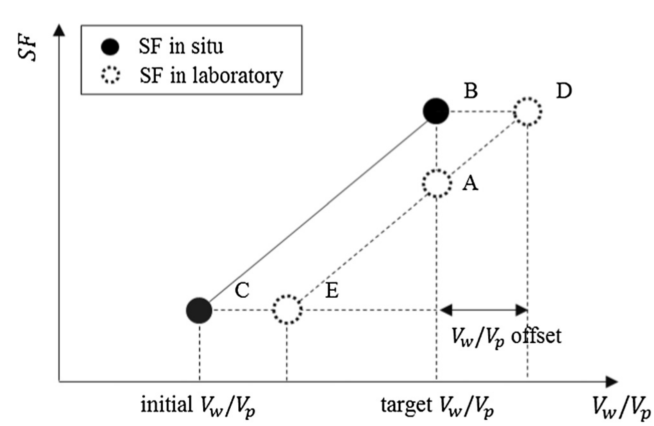

Fig. 1. Fundamental derivation of the proposed moisture estimating method.