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Advanced online water content measurement for self-compacting concrete production in ready-mixed concrete plants

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HIGHLIGHTS

- A calibration method set for industrial measurements of concrete water content was proposed.
- A criterion for identifying the stabilisation of mixer power consumption was suggested.
- Correlation between mixing power and concrete water content was validated in an industrial environment.
- Viscosity agent in SCC increases mixing time and energy consumption.

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ABSTRACT

In ready-mixed concrete plants, the water content of self-compacting concrete (SCC) is generally controlled during the mixing process based on the stabilisation of mixer power consumption. This measurement system is however rarely calibrated, even though its signal is sensitive to the wear of mixers and the temperature of engines.

The aim of this paper is to propose a calibration of mixing power as a measurement of the concrete water content that enables improving water control accuracy. A new approach based on the mixing power evolution is devised for a better determination of the signal stabilisation. The stabilisation time is then defined and considered as the necessary mixing time of each concrete batch. Experimental results obtained from 40 batches of different SCC compositions produced in a full-scale concrete plant have shown that, with the developed calibration method, the stabilisation of power consumption can be considered as a reliable indication of water content with a precision of ±3.8 l/m^3. It is also observed that the water-to-powder ratio (W/P) and the use of viscosity agent have significant effects on the power consumption evolution during mixing.

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1. Introduction

Self compacting concrete (SCC) is considered as an advanced construction material thanks to its high level of workability and good cohesiveness. These properties make it spread easily into place and fill the formwork without any mechanical vibratory consolidation. Many benefits are gained, such as significant reduction in construction time, innovation in architectural features as well as improvement in product quality and working environment. That is the reason why SCC is more and more widely in use in today's construction market.

However, compared with ordinary concretes, the industrial production of SCC requires greater competence in terms of control accuracy of materials. As a matter of facts, their production does not tolerate any approximation due to the sensitivity to compositional deviations, especially the variation of water dosage [1–3]. A conventional concrete can still maintain its fresh state characteristics even with a deviation of 10 l/m^3 in water proportioning. On the contrary, an excess or a lack of such amount of water might cause segregation or insufficient workability for SCC. The water content deviation is expected to vary within ±5 l/m^3 [4]. The major cause of uncertainty in concrete water content is generally perceived to be the aggregate moisture measurement. Although the use of moisture probes in concrete plant leads to a better control of the aggregate moisture content, the precision of these sensors may be not sufficient to guarantee the consistency of SCC production [5].

For an improvement of SCC production regularity and productivity, the application of inline measurements in quality control has become more and more common in the concrete manufacturing process [6–10]. These inline mixer measurements can be

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classified in terms of workability (e.g. mixing power – "wattmeter") or humidity (e.g. moisture sensors). According to industrial experience, some correlations have been found between mixing power consumption and consistency of produced concrete [11,12]. More recently, the measurement process which works on the basis of the rheological principle (e.g. Viscoprobe), has been developed and widely applied in the production of precast concrete [13,14].

In ready-mixed concrete plants, these measurements assist the operator in the regulation of the batch composition by adjusting water content for the forthcoming batches of a same truck based on the information derived from the current batch [11,15]. Nevertheless, sensor signals are used as relative measurements from one batch to another. The water control accuracy depends significantly on the plant operator's skills [3,15]. Therefore, setting a protocol of calibration for each sensor employed in concrete plants becomes necessary in order to enhance the utility of these measurements. This can lead to an improvement of concrete production regularity. Recently, a calibration method designed for industrial measurements of water content has been established by Cazacliu et al. [16]. In their study, the calibration of wattmeter was primarily done with conventional concretes, but few applications were implemented in the case of SCC mixtures in an industrial environment.

As mentioned previously, the online water correction in the concrete batch can be made on the basis of the sensor signal level. The most current measurement method used to give information about the deviation of water proportioning is based on the stabilisation of mixing power measurement. Another purpose of this measure is to determine the mixing time for a given batch by monitoring the signal evolution. As a general rule, concrete can be discharged when the mixing power reaches the stabilisation level. However, no stabilisation signal criterion is presently in place. Hence, the current approach requires waiting for a relative signal stabilisation before emptying the mixer. This waiting period results in a loss of time and thus a reduction in productivity.

In these contexts, the present paper proposes a calibration procedure set for industrial measurements of SCC water content to improve the accuracy of water content measurement. For an adequate calibration, concrete water content is varied in a sufficient range and determined by aggregate sampling. The aggregate moisture measurement is performed by drying method in parallel with microwave moisture probes.

Once the calibration method is established, a new approach based on the mixing power evolution will be introduced for a better determination of the signal stabilisation which allows optimising the mixing time in concrete production. By setting a criterion for the stabilisation determination, the stabilisation time of power consumption is defined and considered as the sufficient mixing time of each concrete batch. The stabilisation power level determined by this approach will be used as a measurement of concrete water content during the calibration procedure. The relationship between the stabilisation power level and the batch water will be then verified thanks to experimental data obtained from various SCC mix designs in the context of an industrial SCC production. Also introduced in this paper will be the influence of concrete composition on power consumption evolution during mixing. This study contributes to improving the use of mixing power measurements to control the production process.

2. Experimental program

2.1. Concrete production plant

The experimental campaign was conducted in a full-scale concrete plant equipped with a 2 m^3 concrete pan-mixer. The power consumption was recorded by a data-acquisition equipment every 0.5 s. The order of constituent loading and the duration of the loading period set by the plant operator in this concrete plant are given as below:

- Gravel and sand (natural moisture) are first introduced into the mixer.
- The loading of fines (cement and filler) occurs after about 10 s.
- Concrete admixtures premixed with water are introduced after 20 s of dry mixing of coarse aggregates and fine elements.

Liquid components were sprayed onto the upper part of the mixture in 9–11 s approximately, depending on the amount of additional water. As reported by RILEM [17], the mixing time was set to start after loading all the components. For all batches of SCC, this mixing time was fixed at 55 s minimum. In reality, there is not a unique mixing time for all SCC mixtures. A long mixing time can be several minutes for more complex mix designs. Therefore, the mixing time was set long enough to avoid incomplete mixing.

The mixing power curve (called "wattmeter curve") of a SCC batch is represented in Fig. 1, which shows the loading sequence and the mixing time. The solid and liquid loadings produce an increase in power consumption. Once the introduction of all components has been completely finished, the wattmeter curve attains its peak. The power consumption then decreases until a stabilisation level is reached. In this plant, the power consumption was measured in percentage of the nominal mixing power of the mixer motor (37 kW). After mixing, the freshly mixed concrete was discharged into mixing trucks and controlled by slump-flow test before delivering to the construction site.

2.2. Measuring and sampling procedure

The natural moisture of sand and gravel contributes to a portion of the mixing water in the batch. The control system takes into account this free water of wet aggregates to adjust water added to the batch. The aim is to batch as close as possible to the reference composition. In consequence, the accuracy in estimating aggregate moisture affects the precision of the water content measurement in batch composition. Unfortunately, the irregularity in aggregate moisture often occurs due to the conditions of production, transport and storage at the concrete plant.

The objective of the wattmeter calibration is to determine the relationship between the stabilisation power level and the concrete water content and then link these two parameters to the workability of SCC. As a result, the batch water content has to be accurately calculated by measuring aggregate moisture. Nonetheless, the production constraints and the lack of measuring instruments do not enable to assess the water content of all aggregate types. Since the coarse aggregate water content, approved by practitioners, fluctuates slightly less than the one of fine aggregate, only two samples of each coarse aggregate were checked for the moisture content before and after each day of production. The wet coarse aggregate dosage calculated by using the average of two measurements was then applied to all SCC batches during a day.

In practice, the water content of the sand varies in a fairly wide range of the order of 1.5–12% [15]. Therefore, it is necessary to precisely estimate the fine aggregate moisture content for every SCC batch. This procedure consists of extracting two samples of each type of sand at the exit of aggregate bins (see Fig. 2) before each produced SCC batch. In order to carry out this step, the concrete plant was operated manually (not in the usual automatic batching procedure). The aggregate loading was delayed for about 2 min. This time interval is long enough to perform correctly aggregate sampling. After that, the batch production followed normal procedures. Based on the maximum aggregate size, the weight of samples is chosen around 1–1.5 kg. Theses samples were then dried by frying pan (at 105 ± 5 °C) in the plant's laboratory in order to determine the moisture content. Depending on the water content, it takes at least 20 min to dry one sample until its change in weight of less than 0.1% [18,19].

All weighing was done by the means of an electronic scale with a precision of ±0.1 g.

In order to conduct the calibration procedure, a large range of variation in fresh concrete water content is needed. In fact, it is not easy to satisfy this condition because in concrete production, plant operators try to maintain the deviation of water content between batches as small as possible. However, we can alternatively set the variation of added water by ±10 l/m^3 for consecutive production batches from the same truck. This way allows guaranteeing adequate water proportioning in the truck and so the concrete can be delivered. In all cases, only batches with volume equals to 2 m^3 were chosen for the study.

Concerning the characterization of SCC workability, an about 10-l concrete sample was extracted from the mixer while emptying in order to measure the concrete slump-flow with Abrams cone test [20]. For practical reasons, slump-flow tests were performed with the cone upside down to make it easier to fill. In addition, a visual stability index (VSI) test was made to identify the segregation risk of SCC mixture during the slump flow test [21]. Each concrete sample was taken directly through the trap-door of the mixer just before falling into the truck to prevent mixing up with the other batches.

2.3. Concrete composition and test samples

In this study, a total of 40 batches from different SCC mix designs were analysed. Four concrete formulas (SCC1, SCC2, SCC3 and SCC4) are given in Table 1. For each mix design, the only factor to vary from one batch to another was water content. While SCC1 and SCC3, characterised by a lower workability, are used for horizontal applications, the two others are employed for vertical applications.

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