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# Effect of particle interlock on flow of aggregate through opening

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ABSTRACT

Blockage of concrete flow through opening or gap often occurs during placement of self-consolidating concrete due to particle interlock of coarse aggregate particles. Suggestions to reduce the coarse aggregate content in order to minimize such particle interlock have been made by some researchers. However, reduction of the coarse aggregate content would also decrease the particle packing density and, if overdone, might adversely affect the overall performance of the concrete. A better understanding of how particle interlock would occur is desperately needed. Herein, a systematic study on particle interlock and flow of aggregate through opening is reported. It will be shown that the aggregate grading has great effects on the flow of aggregate through opening and that to alleviate particle interlock, the fine aggregate content should be more than sufficient to fill the voids between the coarse aggregate particles so as to provide a certain thickness of excess fine coating the coarse aggregate particles.

## 1. Introduction

Due to the resulting faster operation, lower labour cost, lower workmanship demand, lower noise generation and higher reliability, self-consolidating concrete (SCC) is becoming more and more commonly used for construction. However, SCC is by no means simply a high flowability concrete as it is also required to pass through openings and gaps in the mould without vibration. This required property for SCC is widely known as passing ability. In general, it is much more difficult to achieve high passing ability than just high flowability. Depending on the size of the opening/gap and the mix composition of the concrete, the coarse aggregate particles in the concrete tend to pile up in front of the opening/gap to block the subsequent flow of concrete. Such blockage of concrete flow is due mainly to the interlocking action of the coarse aggregate particles and to some extent to the inability of the concrete mix to drag the coarse aggregate particles through the opening/gap, as explained below.

In 1996, Petersson et al. [1] found that the major factors affecting the blockage of concrete flow include the size of opening/gap, maximum size of aggregate, coarse to total aggregate ratio and total aggregate content. They have developed a concrete mix design method for avoiding blockage, which imposes maximum limits on the coarse to total aggregate ratio and the total aggregate content. In 1999, Bui and Montgomery [2] proposed to consider also the cement paste phase in the determination of the maximum total aggregate content for avoiding blockage and achieving certain required flowability. In the same year, Noguchi et al. [3] observed that when concrete flows through a narrow gap, the aggregate particles slow down while the cement paste moves ahead, leading to segregation of the concrete mix and accumulation of aggregate particles at the entrance. Such accumulation of aggregate particles would substantially increase the local aggregate content, thereby hindering or even blocking the concrete flow.

In 2003, Okamura and Ouchi [4] made the recommendation that to avoid blockage of concrete flow, the coarse aggregate content should be limited to 50% of the solid content in the concrete. In 2005, McBride and Mukai [5] studied the effects of the coarse aggregate content, aggregate size and gradation. They found that a smaller aggregate size or a larger aggregate spacing would lead to improved passing ability and that the overall effects of the coarse aggregate are best evaluated in terms of the maximum aggregate size to mean aggregate spacing ratio. In 2006, Ng et al. [6] evaluated the passing ability of various concrete mixes using the U-box and J-ring tests and recommended that the coarse aggregate content should not be higher than the fine aggregate content. In 2007, Sonebi et al. [7] evaluated the passing ability of various concrete mixes using the L-box test and produced a design chart for predicting the passing ability from the water and coarse aggregate contents.

Blockage of flow also occurs when a suspension of solid particles in liquid passes through a porous medium. For this reason, the blockage mechanism has been studied in other disciplines as well. In 2007, Roussel et al. [8], after studying the flow of suspension through porous media in the filtration process, advocated that clogging of a porous medium by solid particles (similar to blockage of flow through opening or gap) is a random phenomenon and therefore a matter of probability. This means that it is not possible to predict precisely whether clogging will occur; what can be predicted is only the probability of clogging. Later, in 2009, Roussel et al. [9] applied their probabilistic approach to study the passing ability of concrete. They pointed out that any segregation induced by the flow through opening or gap may lead to an increase in the local coarse aggregate content, which can by itself increase the probability of blockage. Hence, the risk of blockage is also

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dependent on the segregation resistance, i.e. cohesiveness, of the concrete.

Basically, all researchers recommend the reduction of the coarse aggregate content and/or the total aggregate content to avoid blockage of concrete flow. However, reduction of the coarse aggregate content might decrease the packing density of the aggregate particles and indirectly increase the paste volume needed to fill the voids between aggregate particles. Moreover, reduction of the total aggregate content would directly increase the paste volume needed for the production of the concrete. Hence, if reduction of the aggregate content is overdone, the paste volume can become excessively high, leading to high cost of production and low dimensional stability of the concrete (due to large heat generation at early age and large shrinkage and creep at later age). Good balance has to be maintained between the passing ability of the fresh concrete and the dimensional stability of the hardened concrete. Mix optimization is needed to achieve both high passing ability and high dimensional stability at the same time.

The authors are of the view that the blockage of concrete flow is due mainly to the particle interlocking action of the aggregate particles when they collide with each other at the entrance to the opening/gap. Such particle interlocking action is larger when the opening/gap is relatively small or the particles are relatively large. In theory, the addition of more paste to reduce the concentration of coarse particles can help to reduce the frequency of collision between the coarse particles and thus mitigate the particle interlocking effect. However, it is actually the local concentration of coarse particles at the entrance that matters. Although the addition of more paste can reduce the average concentration of coarse particles, since the paste tends to move ahead of the aggregate particles at the entrance, the local concentration of coarse particles there can still be quite high. Herein, it is postulated that for reducing the particle interlocking action, the addition of more paste is not the best solution. Instead, the addition of more fine particles to reduce the concentration of coarse particles should be a better way, for the following reasons. First, the fine particles would move together with the coarse particles when passing through the opening/gap. Second, the fine particles would act as ball bearings at the surfaces of the coarse particles to alleviate the particle interlocking action. Third, the addition of more fine particles would increase the cohesiveness so that the concrete mix is more able to drag the coarse particles through the opening/gap.

To verify the above postulations and study how best to reduce the particle interlocking action, a comprehensive research programme has been launched. The research programme was conducted in two phases. The first phase, as reported herein, was on the flow rate of blended aggregate through a V-funnel. The second phase, to be reported later, was on the flow rate of concrete through the same V-funnel. In the first phase, the flow rate was purposely measured with no paste added so that the variation in flow rate is due entirely to the particle interlocking action. Actually, the flow of granular materials through a funnel or hopper has been studied in other disciplines, especially chemical engineering, and it has been found that blending of two or more granular materials of different sizes together can significantly increase the mass flow rate through opening/gap [10,11]. More importantly, when granular materials flow, dilation occurs and such dilation has significant effect on the mass flow rate [12,13]. Somehow, there have never been any similar studies in concrete technology research using rock aggregate as the granular material.

## 2. Experimental programme

### 2.1. Aggregate samples tested

The aggregate employed for testing was crushed rock aggregate of granite origin. It was obtained from the market and thus should be representative of crushed rock aggregate being used for the production of concrete. Its saturated solid density and oven-dried solid density have been measured in accordance with BS 812: Part 2: 1995 [14] as 2609 and 2590 kg/m$^3$, respectively. After one month of conditioning and air drying in the laboratory, the aggregate was measured to have a moisture content of 0.27%. Hence, its air-dried solid density may be calculated as 2597 kg/m$^3$. According to BS 812: Part 102: 1989 [15], the aggregate may be described as “angular”. Using the methods stipulated in BS 812: Part 105: 1990 [16], the flakiness and elongation indices of the 14–20 mm size fraction have been measured as 15 and 12, while those of the 10–14 mm size fraction have been measured as 14 and 27.

From the aggregate, seven size classes of aggregate particles were produced by mechanical sieving. The seven size classes were named as S1, S2, S3, S4, S5, S6 and S7, which were the respective portions of the aggregate retained on the sieves of size 300 μm, 600 μm, 1.18 mm, 2.36 mm, 5 mm, 10 mm and 14 mm after sieving, as tabulated in Table 1. Each size class has a narrow range of particle size from the size of the sieve it was retained on to the size of the next larger sieve it passed through and thus may be regarded as single-sized. For simplicity in later analysis, each size class is taken to have a particle size equal to the geometric mean of the lower and upper size limits of the particle size range, as listed in the fourth column of Table 1.

From the seven size classes, different combinations of a larger size class and a smaller size class were blended together to form binary blended aggregate samples for testing. As presented in Table 2, the aggregate samples may be broadly divided into three groups. For the first group, S5 was blended with S1, S2, S3 or S4. For the second group, S6 was blended with S1, S2, S3, S4 or S5. For the third group, S7 was blended with S1, S2, S3, S4, S5 or S6. In total, there were 15 combinations, each referred to as Sx–Sy, in which Sx is the name of the larger size class and Sy is the name of the smaller size class. Furthermore, for each combination, the two size classes were blended at different proportions ranging from 0 to 100% in steps of 10%. Altogether, 7 non-blended aggregate samples and 135 binary blended aggregate samples were formed for testing. In each aggregate sample, the proportion of the larger size class is referred to as the coarse content while the proportion of the smaller size class is referred to as the fine content. Both the coarse and fine contents are each expressed as a percentage by solid volume of the total aggregate content.

### 2.2. Testing procedures

The aggregate was first conditioned and air-dried in the laboratory for one month. Then, it was divided into seven size classes by mechanical sieving. From the seven size classes, the 7 non-blended aggregate samples were obtained directly while the 135 binary blended aggregate samples were obtained by mixing manually a larger size class Sx and a smaller size class Sy together as per the combinations depicted in Table 2 at different proportions.

Each aggregate sample, whether non-blended or blended, was subjected to the V-funnel flow test to measure its flow rate and the packing density test to measure its packing density. The V-funnel flow test and the packing density test were carried out simultaneously. This was done by placing the steel container for packing density measurement underneath the opening of the V-funnel. In this way, the aggregate

**Table 1**
Seven size classes of crushed rock aggregate.

| Size class | Sieve size range | | Geometric mean size | Aggregate size to opening size ratio |
|---|---|---|---|---|
| | Sieve retained on | Sieve passed through | | |
| S1 | 300 μm | 600 μm | 0.42 mm | 0.006 |
| S2 | 600μm | 1.18 mm | 0.84 mm | 0.011 |
| S3 | 1.18 mm | 2.36 mm | 1.67 mm | 0.022 |
| S4 | 2.36 mm | 5 mm | 3.44 mm | 0.046 |
| S5 | 5 mm | 10 mm | 7.07 mm | 0.094 |
| S6 | 10 mm | 14 mm | 11.8 mm | 0.158 |
| S7 | 14 mm | 20 mm | 16.7 mm | 0.223 |