Mix design and material selection

Aggregate: a key ingredient of Self-Consolidating Concrete

Self-consolidating concrete (SCC) is a highly flowable yet stable concrete. As high flowability and stability are contradictory properties, SCC is highly sensitive to material type and proportion. An important ingredient of SCC is aggregate, as it occupies 60 to 70% of the concrete’s volume. Therefore, it is essential to study how aggregate characteristics affect the flowability and stability of a SCC mix. This investigation focused on the effect of fine aggregate grading on the performance of fresh SCC. The results indicate that to obtain a high-quality SCC product, aggregates should have a certain maximum size and distribution. However, the effect of poor aggregate grading may be alleviated by proper combination of fine and coarse aggregates. The paper also presents a case study on the development of high strength SCC made with poorly graded fine and coarse aggregates. In this project, the total aggregate grading was influenced by adjusting the sand-aggregate ratio.

Self-consolidating concrete (SCC) is a highly flowable yet stable concrete, of high flowability together with remarkable stability. Flowability of SCC can easily be achieved by increasing the water content or incorporating proper admixes. But, providing adequate stability is more difficult and requires special attention to mix materials and proportion [1].

As the fluidity increases, the risk of instability increases. Instability can occur in various forms such as segregation, blocking and bleeding. Segregation is defined as the separation of granular particles from the mortar matrix during transport, placement, and casting (dynamic state), or after concrete placement (static state). A fresh SCC with poor segregation resistance can lead to a non-uniform distribution of coarse aggregates in the concrete skeleton, and even non-uniform mechanical properties and durability in the hardened state [1, 2].

Another category of instability is local aggregate separation and blocking, which occurs while concrete flow across obstacles. This type of instability should be carefully avoided in SCC, since one of the major applications of SCC is placement in narrow sections and members with congested reinforcement, and no vibration energy exists to dislodge these blockages [2, 3]. Highly flowable mixes are also prone to excessive bleeding. Bleeding, which is related to water migration, can weaken the quality of the interface between aggregate and cement paste, and deteriorate the impermeability and mechanical properties [4].

To alleviate heterogeneity problems of highly flowable concrete, proper selection of constituents and mix proportions is crucial. An important ingredient of SCC is aggregate, as it occupies 60 to 70% of concrete volume. Aggregate size, shape, angularity and texture as well as the grading are important factors that should be carefully adjusted to ensure the required stability level in a SCC mix [5, 6]. Therefore, to be able to offer a high-quality SCC product, it is essential to have understanding and knowledge of how aggregate characteristics affect the flowability and stability of fresh SCC.

The main objective of this study is to investigate the effect of aggregate grading on fresh properties of SCC. Since SCC is usually made with smaller maximum aggregate size and higher fine aggregate content, the effect of fine aggregate properties on concrete workability is more important than the effect of coarse aggregate properties [7, 8]. In this study, the effect of aggregate maximum size (Dmax) and distribution on the fluidity and stability of self-consolidating mortar has first been investigated. Next, the effect of fine aggregates with different Dmax on the fresh performance of SCC mixes is studied. Furthermore, a case study of the applicability of poorly graded aggregates in producing high strength SCC is presented.

Experimental program

The experimental program consisted of two phases. The first phase or mortar phase concerned the effect of maximum aggregate size (Dmax) and distribution on fresh properties of self-consolidating mortars, while the second phase (concrete phase) dealt with the effect of aggregate properties on self-consolidating concrete.

Mortar phase

Six different aggregate gradings were considered in the first phase. The used aggregate consisted of three different maximum sizes (Dmax = 2.36, 4.75 and 9.5 mm), each of which had two different gradings, an S-shaped grading and a concave grading, as shown in Fig. 1. As shown in the figure, the S-shaped grading refers to well-graded materials containing more fine and less coarse aggregates, compared to concave grading. The concave grading indicates that a low fraction of aggregates passed the coarse sieves, and therefore the aggregate is relatively coarse.

The relative volume of water, cement, aggregate and chemical admixes was kept constant in each series of mortar mixes. The main varied parameter was the aggregate grading as shown in Fig. 1. All mixes were designed with Water-Powder Material ratios of W/PM = 0.4 and W/PM = 0.5, which were labeled as L1 to L6 and H1 to H6, respectively. Details of mix proportions are summarized in Table 1. The mixes correspond to the mortar in concrete with Dmax = 19 mm, fine/total aggregate = 60%, and cement content of 450 kg/m³, which is quite common for self-consolidating concrete.

![Fig. 1: Aggregate size distribution](image)
Concrete Phase

The second phase of this study investigates the influence of fine aggregate grading on the fresh properties of SCC mixes. The used fine aggregates were Sand #2 and Sand #4, which had different maximum sizes and particle distributions, while the coarse aggregate had the same grading in all the mixes. Since the effect of fine aggregate grading might be influenced by fluidity, for each grading two SCC mixes with slump flow consistencies of 575 ± 25 mm and 725 ± 25 mm were prepared. For all SCC mixes, the cement content was generally maintained at 400 kg/m³ and the water content was adjusted to reach the target fluidity. The ratio of fine to total aggregate was about 53% and limestone powder was used at 200 kg/m³. The mix design of the SCC mixes is summarized in Table 2.

Tests

In the first phase, mini-slump flow, mini-V-funnel, and mini-column segregation tests were performed to investigate fresh properties of mortar mixes; mini-slump flow test for evaluating fluidity and edge...
bleeding, mini-V-funnel test for evaluating viscosity and blocking, and mini-column segregation test for evaluating static segregation. Among these tests, mini-slump flow and mini-V-funnel were conducted in accordance to EFNARC [9], while the mini-column segregation test was similar to ASTM C1610, but in a smaller size [10].

In the second phase, slump flow, V-funnel, L-box and U-box tests were performed on self-consolidating concretes; the slump flow test for evaluating the fluidity, the V-funnel test for estimating the viscosity and the ability to pass through a constricted area, the L-box test for evaluating the passing ability through closely spaced reinforcing obstacles, and the U-box test for evaluating the passing ability through a narrow opening under a particular head of fresh concrete.

Results and discussion

Results of the mortar phase

The slump flow of mortar mixes with different Dmax is presented in Fig. 2. This figure shows both homogeneous spread diameter and edge bleeding. The results indicate that increasing the maximum size of the aggregates tends to increase the fluidity of all the mixes. This may be due to the fact that the specific surface area of aggregates will decrease by increasing Dmax. The retained water can participate in lubricating the mix, thus improving the fluidity. On the other hand, when the aggregates get coarser, the risk of instability will increase. The experimental results show that excessive bleeding appears in all the mixes made with Dmax=9.5 mm. Mortar mixes with Dmax=4.75 mm also exhibit some signs of bleeding. As expected, much more bleeding occurs in the mixes with higher W/PM. However, no bleeding is observed in both Dmax=2.36 mm mixes. It is also worthwhile to note that the increased fluidity of the mixes with Dmax=9.5 mm is mainly due to the induced bleeding. The induced bleeding reduces the homogeneity and deteriorates the workability of the mixes. So, the increased slump value does not necessarily indicate improved workability.

Comparing Fig. 2a to Fig. 2b, and also Fig. 2c to Fig. 2d shows that the fluidity of the mortar mixes is not significantly influenced by the

<table>
<thead>
<tr>
<th>Label</th>
<th>Sand Grading</th>
<th>Cement (kg/m³)</th>
<th>Limestone Powder (kg/m³)</th>
<th>W/PM</th>
<th>Slump Flow (mm)</th>
<th>Super Plasticizer (kg/m³)</th>
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<td>700</td>
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</table>

Fig. 2: Mini-slump flow and mini-V-funnel results of mortar mixes made with different aggregate gradings
curvature of aggregate grading. However, mortar mixes made with concave aggregate grading may exhibit slightly more bleeding compared to mortar mixes made with S-shaped aggregate grading with the same D_max. This may be due to the coarser particle size of concave grading in comparison with S-shaped grading.

The flow time of the mortar mixes is also presented in Fig. 2. The results show that increasing the maximum size of the aggregates decreases the flow time of the mortar mixes. Furthermore, mortar mixes with S-shaped aggregate grading, which contains more fine
aggregate, seem to have a higher flow time compared to mixes made with concave aggregate grading. However, all the mixes with D\textsubscript{max}=9.5 mm were blocked during the flow through the outlet gate of the V-funnel. Blockage also occurred in mortar mixes with D\textsubscript{max}=4.75 mm and W/PM=0.5, which indicates low cohesiveness of these mixes.

The static segregation results of the mixes, measured with the mini-column segregation apparatus and quantitatively described by the segregation index (SI), are presented in Fig. 3. It is apparently evident that the SI of mixes is rapidly increased by increasing the maximum size of the aggregate. On the other hand, comparing the results presented in Fig. 3 shows that the risk of static segregation in mortars with concave aggregate distribution is generally higher than in mortar mixes with S-shaped aggregate grading. It is mainly due to the fact that the average diameter of concave grading is larger than that of the S-shaped grading. When the aggregates get coarser, the bond between the solid phase of the mix and the paste decreases. Therefore, the ability of the paste to maintain the aggregates will reduce, and settlement of coarse aggregates will occur.

Based on the obtained results, increasing D\textsubscript{max} of the aggregates may be useful for improving the fluidity of mortar mixes. On the other hand, the results show that the worst case to handle, from a stability point of view, is the case with the coarsest aggregate. So, the increase of segregation, bleeding and blocking imposes limitations on D\textsubscript{max}. In the cases where coarser aggregates should be used in the mix due to mechanical requirements and/or economical aspects, more effort should be made to tackle the issue of induced segregation, bleeding and blocking. One way for reducing the risk of instability in the mixes with larger D\textsubscript{max} is modifying the aggregate size distribution and using a S-shaped grading. The results presented in Fig. 3 indicate that the SI of the S-shaped mix is about 20% lower than those mixes made with the same D\textsubscript{max} and concave grading. Other possible ways to mitigate the risk of instability may include reducing the W/PM or the use of mineral admixtures or VMAs [10, 11]. Reducing W/PM and/or utilizing VMAs could increase the viscosity and reduce the risk of bleeding and segregation while incorporating proper types and amounts of mineral admixtures increases the paste volume and adjusts its composition and therefore enhances both bleeding and blocking characteristics.
Results of the concrete phase

The required water content and V-funnel flow times of mixes with slump flow values of 575 ± 25 mm and 725 ± 25 mm are shown in Fig. 4. As shown in the figure, the obtained results are almost the same as those obtained in the mortar phase. As expected, SCC mixes made with finer aggregates require more water to reach the same level of fluidity. That means increasing the Dmax improves fluidity of the mixes. On the other hand, increasing Dmax of sand deteriorates the passing ability of the concrete. The results show that all mixes made with D_{max} = 2.36 mm sand passed through the V-funnel gate while both SCC mixes made with D_{max} = 4.75 mm sand were blocked during flow through the restricted apparatus. That means increasing the Dmax increases the risk of local aggregate separation and segregation in the outlet gate of the V-funnel.

The results of L-box and U-box tests are presented in Figs. 5 and 6. Based on the obtained results, the h2/h1 is almost the same for all the mixes. However, obvious blocking of aggregates behind the reinforcing bars of the L-box could be detected visually for the SCC mixes made with sand of D_{max} = 4.75. The heterogeneous flow of SCC mixes made with D_{max} = 4.75 sand is also detected by the U-box test results which are plotted in Fig. 6. The heterogeneous flow of SCC mixes with slump values of 725 ± 25 mm through the reinforcement of the L-box test is shown in Fig. 7.

The obtained results of SCC mixes with different fine aggregates indicate that SCC mixes made with finer aggregates require more water to reach the same level of fluidity compared to mixes with coarser aggregates. However, the use of finer aggregate significantly increases the stability and passing ability through narrow sections and congested reinforcement.

Case Study

As part of a construction program for the Omid official building in the center of Tehran involving the use of new technologies, high-strength SCC was selected to demonstrate for the first time in Iran the applicability of such material for the casting of heavily reinforced concrete structures. The unique feature of this project was the construction of a 21 stories, moment resistant steel frame on top of a 6 stories concrete structure. The transition story between the steel and concrete structures (sixth story) includes 48 composite columns, each 900 × 900 mm², and consists of cross-shaped steel profiles and heavily reinforced concrete. The structural design specified longitudinal reinforcement consisting of 16 bars of 25 mm diameter, distributed around a cross shaped steel section which could result in a minimum spacing of 30 mm in the special zone. Therefore, the concrete had to be able to flow through a 30 mm gap without blocking or segregating. Besides, the concrete should completely fill the bottom of the shear keys ensuring the proper anchorage of the steel section to the concrete column. The minimum clear cover was specified to be 35 mm. The resulting reinforced section presented serious obstacles for the deformability of the concrete, especially given the limited cover over the reinforcement (35 mm). The column section is shown in Figs. 8 and 9. The minimum specified 28-day compressive strength was 60 MPa, which is required due to the critical load transition between the steel and concrete structures. Other factors that had to be taken into account in the concrete design included the ambient temperature range of 5 to 35°C during the construction period.

One of the major restrictions encountered using SCC in this project was the poor grading of aggregates, which significantly increased the risk of segregation (Fig. 10). Under such conditions, a proper combination of fine and coarse aggregates and incorporating ade...
Adequate amount of fillers helped to overcome such limitations in the case study presented here. The fine aggregate was river sand with a maximum size of 4.75 and a fineness module of 3.91. The coarse aggregate was in the range of 12-25 mm. To alleviate the heterogeneity problems resulting from the use of poorly graded aggregates, several trial mixes were prepared in the laboratory, and the optimum fine/total aggregate ratio was investigated. Based on the empirical results, the fine/total aggregate ratio was set to 70% to reduce the risk of blockage through narrow rebar spacings. A high binder content of 550 kg/m³ was used to increase the paste volume; however, the content of cement was limited to 440 kg/m³ to avoid increased hydration temperatures. The binder incorporated 20% of a Class F fly ash replacement. The Water-Powder Material ratio was set at 0.27 to ensure the concrete passes the strength criteria. A Polycarboxylic acid superplasticizer (1.7% by weight of cement) was used to enhance the fluidity of the fresh concrete. The mix proportion of the recommended SCC is given in Table 3.

The proposed mixes had slump flow and J-ring results of 750 mm and 10 mm, respectively. The concrete was cast directly into the column through an inverted cone hopper. The concrete spread readily along the length of the form and around the cross shaped steel column and achieved good filling of the formwork. Neither visible
aggregate segregation nor surface bleeding was observed during or after the concrete placement. All concrete columns were cured for a minimum of 7 days after placement. The average compressive strengths at 28 days were 75 MPa. Despite the high content of cementitious materials, no substantial increase in concrete temperature was recorded during the curing procedure.

Conclusions

Based on the results of this study, the following conclusions can be drawn:

- Increasing the maximum size of the aggregates may be effective for improving the fluidity of cementitious mixes. However, the use of coarser aggregates increases the risk of bleeding, segregation and blockage of cementitious mortars and deteriorates the passing ability and stability of concrete mixes.

- The increased risk of instability in the mixes with larger D_max might be alleviated by modifying the aggregate size distribution and using S-shaped grading curves. The experiments presented herein indicate that the stability of S-shaped mixes is about 20% lower than mixes made with the same D_max and concave grading.

- In the cases where using aggregate with proper maximum size and distribution is not possible, the adjustment of the fine to coarse aggregate ratio may be effective for achieving a stable SCC. Other possible ways to mitigate the risk of instability may include reducing the W/PM or the use of mineral admixes and/or VMAs.

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References