Assessment of Changes in Compressive Strength of Deep Beam Elements Made by Pumping Self-Compacting Concrete Bottom-Up

Piotr Dybel 1
1 AGH University of Science and Technology, Department of Geomechanics, Civil Engineering and Geotechnics, al. Mickiewicza 30, 30-059 Cracow, Poland
dybel@agh.edu.pl

Abstract. This experimental work investigates into the effect of a change in the compressive strength of concrete along the length and height of monolithic deep beams made of high performance self-compacting concrete (HPSCC). In the tests, three different HPSCC mixes were used in which the amount of silica fume differed (0, 5 and 10% by mass of cement). The binder content (550 kg/m 3) and the water-binder ratio (0.32) were fixed. Experimental deep beams, measuring 1.60 m in length, 0.16 m in width and 0.48 m in height, were cast. Two variants of concrete mixture casting were considered in this work: from the top and from the base of the formwork system with a single casting point at one edge. No significant changes to the compressive strength along the element span were observed in the tests, independently of the casting variant or the mixture composition. However, a tendency was observed for the compressive strength to undergo a reduction with an increasing distance between the samples and the concrete casting point. On the other hand, the tests showed that independently of the concrete casting variant, the mixture composition or the distance to the concrete casting point, in the upper parts of the elements there was a concrete layer of poorer quality and lower compressive strength. The reduction of the compressive strength of the top sample with respect to the bottom one was in the range 6.1 - 15.0% for the top-down concreting and 1.0 - 10.3% for concreting from the bottom of the formwork. Casting the self-compacting mixture from the bottom of the formwork yielded a satisfactory degree of the strength homogeneity in the test element. This variant of casting may be used in practice as an alternative way of laying an self-compacting concrete mix.

1. Introduction
The continuous development of concrete technology over the last decades has given birth to new generation concretes with qualitatively better properties not only in terms of strength and durability, but also rheology [1, 2]. Self-compacting high performance concretes (HPSCC) fall in this category and have been designed based on self-compacting concretes (SCC) and high performance ones (HPC). When compared to normal concretes, high performance concretes are characterized by better strength and durability. Self-compacting concretes, on the other hand, in comparison to traditional concretes exhibit special rheological properties that secure gravity-assisted shape-independent mould or formwork filling in absence of segregation and with no need for extra mechanical compaction [3–5]. In contrast to vibrationally-compacted concrete, the HPSCC’s capability to spread over much greater distances allows reducing the number of concrete-casting points while producing a concrete element [6, 7]. It is possible
to fill all the mould tightly from just a single casting point (e.g. beams, deep beams) or reduce the number of concrete drop points by letting the mixture spread as far as possible before switching to the next point (e.g. slabs, walls).

Exceptional rheological features of self-compacting mixtures enable formwork filling both bottom-up and top-down. A traditionally-followed method these days is to distribute a mixture form the top of a mould. Alternatively, casting a mixture from the bottom can be carried out by pumping it through a special valve installed permanently in the system formwork. The latter approach is favourable when forming vertical elements, such as walls or pillars of complex geometry, dense reinforcement or with problematic access from the top [8]. The bottom-up mix casting scenario facilitates mix venting and in consequence leads to better finishing of the concrete surface. What is more, continuous mix rising in the mould decreases the risk of segregation [9]. Thus, one may suspect that the bottom-up concrete casting version should lead to a more uniform distribution of strength properties in the final concrete element than in the case of casting from the top. However, there are no research works confirming this hypothesis.

2. Scope of research
This work attempts to evaluate the distribution of strength-related parameters of new generation HPSCC in an element where the concrete mix was cast from the top as well as from the bottom of a mould from a single point situated at one edge of this element. In particular, the spatial variation of the compressive strength was investigated. In the tests, 216 cubic specimens were used that had been cut out of deep beams made of three different mixes of HPSCC. The compressive strength tests were conducted according to EN 12390-3 [10]. The tests were carried out after 28 days of concrete curing in laboratory conditions.

3. Experimental program
3.1. Concrete mixtures
The study was performed on elements made of three HPSCC mixtures in which the amount of silica fume varied (0, 5 and 10% of cement mass), replacing part of the concrete. However, the binder content (550 kg/m³) and the water-binder ratio (0.32) were constant. The composition of mixes was developed based on own experiences and work guidelines [3–5, 11]. The characteristic properties of the concrete mixes are given in table 1.

| Composition by mass of proposed mixes. |
|-----------------------------------------|
| Recipe denotation | HPSCC-0 | HPSCC-5 | HPSCC-10 |
| Cement CEM I 42.5R | 550 | 524 | 500 |
| Water | 176 | 176 | 176 |
| Sand 0-2 mm | 790 | 790 | 790 |
| Basalt aggregate 2-8 mm | 940 | 940 | 940 |
| Silica fume | – | 26 | 50 |
| Superplasticizer | 5.14 | 5.98 | 6.27 |
| Water/binder ratio | 0.32 | 0.32 | 0.32 |
| Silica fume level | 0% | 5% | 10% |

3.2. Description of specimens
Deep beam-type study elements having dimensions of 1.60 x 0.16 x 0.48 m (length x width x height) were used in this project. Each element was designed so that its dimensions were multiplicities of the dimensions of a cubic specimen (0.16 x 0.16 x 0.16 m). Concreting of the elements was carried out in two variants of concrete mix casting:

- variant I - casting from the top of the mould from a single point at an element’s edge,
- variant II - casting from the bottom of the mould from a single point at an element’s edge.
Variant II was realized by casting the concrete mix to specially prepared piping extending over the upper level of the mould. In the process, the concrete mixture was filling the mould under its own weight just like in communicating vessels. For each HPSCC two study elements were made following the casting variant under consideration. The concreting was performed continuously until the formwork was full. Figure 1 shows a schematic view of the study element. The concreted deep beams were left for 3 days in the formwork. After formwork removal the elements were kept in a lab room in unchanged positions. Prior to analyses, the elements were protected against vibrations and under constant care through water spraying. After 21 days, the specimens were cut into elementary parts. All the specimens from the middle layer and selected specimens from the bottom and top layers (the specimens from columns 2, 4, 6, 8) were used in the analysis described in this article. Additionally, five reference specimens were also made for each concrete type. Compressive strength tests were done according to EN 12390-3 [10].

![Figure 1. Schematic view of test element.](image)

4. Results and discussion
The results concerning the rheological properties obtained for the concrete mixes and the average values of the compressive strength for the reference specimens are presented in table 2. Tables 3 and 4 show the results on the compressive strength of the concrete specimens taken from the study element. Figure 3, on the other hand, presents the variation of the compressive strength ratio along the study element defined for a given layer as the ratio of the compressive strength of a given specimen and that of the specimen situated at the casting point (\( f_{c,i} / f_{c,1} \)).

| Mix symbol | Slump flow [mm] | Slump flow class | Slump flow time T50 [s] | Viscosity class | L-box ratio | L-box visual stability index | Compressive strength \( f_c \) [MPa] | Cov [%] |
|------------|----------------|------------------|-------------------------|----------------|-------------|-----------------------------|-------------------------------|-------|
| HPSCC-0    | 680            | SF2              | 2.1                     | VS2            | 0.93        | PL2                         | 84.9                          | 7.3   |
| HPSCC-5    | 660            | SF2              | 2.8                     | VS2            | 0.90        | PL2                         | 90.1                          | 3.3   |
| HPSCC-10   | 710            | SF2              | 2.5                     | VS2            | 0.89        | PL2                         | 91.7                          | 5.4   |

The tests have not revealed any significant changes of the concrete’s compressive strength along the study elements. This was true regardless of the direction of mix casting, the HPSCC mix composition or the layer under consideration (top, middle, bottom). The compressive strength variation coefficient (Cov) of the individual layers ranged, depending on the mix type, between 0.8 and 3.9% for the top-down concreting and from 0.9 to 3.4% for the bottom-up concreting. Moreover, the tests have demonstrated correspondence between the compressive strength distribution and the concrete volume density distribution along the elements.
The studies have not revealed any significant impact of the concrete mix casting direction on the values of the compressive strength. However, in the case of casting from the bottom of the mould, the top layer specimens exhibited higher compressive strength as compared to the top specimens concreted in the traditional way. The average increase of the compressive strength in the top layer was 5%. This effect was independent of the HPSCC type.

The compressive strength values obtained for the specimens cut out of the study elements have been compared to those measured for the reference samples produced in accordance with [10] (figure 2). Only the top layer specimens in the study element exhibited lower values of the compressive strength comparing to the compressive strength of the reference samples. Such a situation was observed regardless of the concrete casting direction or the HPSCC composition. The maximum difference of the compressive strength was 10%. This is caused by a higher mix consolidation degree in the reference samples comparing to the top layer of the study element.
Figure 2. Compressive strength as a function of specimen position

Figure 3. Variation of compressive strength along the length

The HPSCC concretes used in the experiment did not exhibit statistically important differences in the compressive strength of the study elements. Furthermore, no significant variation of the compressive strength with the distance of a specimen from the concrete casting point was observed. This tendency was independent of the direction of concrete mix casting and mix content. When casting top-down, the
The compressive strength ratio was in the range 0.90-1.05 with an average of 0.98. In the case of the bottom-up casting, the compressive strength ratio varied between 0.94 and 1.08 and the average value was 1.01.

However, the studies have shown that the concrete’s compressive strength suffers a reduction as the distance of a specimen from the bottom of the formwork increases. Regardless of the concrete casting direction and mix composition or the distance from the casting point, in the top parts of the elements there was a concrete layer having poorer quality and lower compressive strength. Figure 4 shows the changes of the compressive strength ratio along the height of the element ($f_{c,h}/f_{c,bottom}$). The compressive strength reduction between the top layer specimens and the bottom layer specimens varied between 6.1 – 15.0% in the top-down concreting variant, and between 1.0 – 10.3% for the bottom-up case. The average value of this reduction was 10.8% and 6.1% for the top-down and bottom-up scenarios, respectively.

![Figure 4](image_url)

**Figure 4.** Variation of the compressive strength ratio along the heights of the elements.

The results indicate that in the case of the elements concreted bottom-up the compressive strength is more uniform along their heights than in the case of traditionally-made elements. The physical basis of the compressive strength reduction is the effect of a specific form of segregation related to free water self-draining. The potential entrapment of bleed water underneath coarse aggregate particles can be expected to increase towards the top of the deep beam. Such bleeding can weaken the interface between the aggregate and cement paste and result in a reduction of compressive strength. These phenomena are curbed in the case of the alternative concrete casting scenario. Concreting from the bottom of a mould...
enables self-venting and self-consolidation of a concrete mix. This leads to a reduction of the number of air bubbles in the interface between the aggregate and cement paste and results in decreased mix sedimentation under the aggregate.

No relation has been found between the compressive strength along the element’s height and the distance of the specimens from the concrete casting point. This observation was independent of the mix casting direction. It is connected to a uniform strength distribution along the element both in its top part and in the bottom part.

5. Conclusions

The main scope of the present study was the compressive strength variation along the length and the height of monolithic deep beams where the concrete mix was cast from the top and from the bottom of a mould with a single casting point at edges of the elements. The following conclusions can be drawn from the results of this experimental work:

- Statistically insignificant differences were obtained between the variations in the compressive strength values along the 1.60 m-long deep beams made of HPSCC mixtures. In general, the variations in the compressive strength along the length of the experimental elements were limited to 10% in the case of casting from the top of the mould and 6% when casting bottom-up.

- It was demonstrated that independently of the concrete casting variant, the mixture composition or the distance to the concrete casting point, in the upper parts of the elements there was a concrete layer of poorer quality and lower compressive strength. The reduction of the compressive strength of the top sample with respect to the bottom one was in the range 6.1 - 15.0% for the top-down concreting and 1.0 - 10.3% for concreting from the bottom of the formwork.

- Casting the self-compacting mixture from the bottom of the formwork yielded a satisfactory degree of the strength homogeneity in the test element. This variant of casting may be used in practice as an alternative way of laying an self-compacting concrete mix.

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