Composite SCC and 3-D-Printed Concrete Columns

by Johan L. Silfwerbrand

In 2024, the concrete industry marked the 200th anniversary of Joseph Aspdin's patent for portland cement. The methods used to produce concrete have developed successively since then, and much research currently focuses on reducing concrete's climate footprint, primarily by replacing parts of cement with industrial by-products and other alternative binders (supplementary cementitious materials [SCMs]).

In recent decades, new techniques have also been developed to produce concrete. Compaction through vibration, which is a labor-intensive job, can now be omitted through the use of self-consolidating concrete (SCC) or through the application of three-dimensional (3-D) printers. In the research project presented herein, both techniques have been combined in the casting of columns.

Traditionally, concrete columns have been produced by placing concrete into a mold or form made either of wood or steel. While steel molds can be used many times, wooden molds can at best be used two or three times. For either material, building and then removing the formwork takes time and labor, and eventual replacement of the formwork leads to increased material use and transport costs. A new alternative, investigated in this project, is a permanent 3-D-printed concrete (3DPC) form in which a core is cast with SCC.

The 3DPC can serve to protect reinforcement from corrosion and fire. If composite action between the 3DPC and the SCC in the column can be proven, the entire composite cross section can be taken into account for load-carrying capacity, providing further justification for the omission of the expensive and labor-intensive formwork.

One problem with current 3DPC technology is its high cement content due to the small maximum aggregate size required by most printing nozzles. However, if the 3DPC shell can be made thin and its high cement content can be used to provide a dense concrete cover for reinforcement in an SCC core with moderate cement content, the total cement content per composite column volume may be comparatively low, resulting in a durable and sustainable solution.

To study both load-carrying capacity and durability of such columns, tests on six columns and many cores were performed at the KTH Royal Institute of Technology (KTH), Stockholm, Sweden, in cooperation with Research Institutes of Sweden (RISE) and two Swedish companies, ConcretePrint and Heidelberg Materials Betong Sverige.

Previous Research

Composite columns made of 3DPC forms and SCC cores have been previously investigated by a limited number of researchers.[1-5] References 1 and 2 deal mainly with the architectural and aesthetic possibilities that this technology offers.

Zhu et al.[3] tested 600 mm (24 in.) tall composite and homogeneous 250 mm (10 in.) diameter columns with promising results. Their loading test results indicated that the 25 mm (1 in.) thick 3DPC form contributed to the load-carrying capacity of the composite column.

Chen et al.[4] tested 630 mm (25 in.) tall composite concrete columns with a square-shaped cross section and a side length of 280 mm (11 in.). The authors disregarded the contribution of the 60 mm (2.4 in.) thick 3DPC form when calculating the load-carrying capacity, but the measured failure loads indicated that the form contributed substantially.

At KTH, two pilot studies were performed prior to the current research project.[6] The aim was to study the possibilities of producing composite columns made of 3DPC forms filled with SCC. In the second pilot study, three 500 mm (20 in.) diameter and 2.4 m (8 ft) tall composite columns were cast. The thickness of the 3DPC form was 50 mm (2 in.). The tests showed that it was possible to produce these composite columns (the pressure exerted by the SCC did not lead to cracking or leakage of the 3DPC form). The promising results from the pilot studies led to a larger research program, which is described in the following section.

Research Program

The research consisted of 15 steps (refer to Table 1) conducted between August 2023 and January 2024. Both the 3DPC forms and the SCC cores of the composite columns, as well as test specimens for strength and durability tests, were cast at Heidelberg's ready mixed concrete plant in Tumba, a southern suburb of Stockholm. The loading tests of the columns were carried out at RISE's structural engineering laboratory in Borås, 405 km (251 miles) southwest of Stockholm. The mixture proportions for the 3DPC and SCC are listed in Table 2. The intended strength class of the SCC was C28/35 according to the European standard (aiming at a

Table 1:
Steps and dates

No.	Step	Date	Age*, days
1	Printing of 3DPC forms	August 23, 2023	—
2	Installing reinforcement with strain gauges	September 2023	—
3	Casting of cylinders using the 3DPC mixture	September 14, 2023	—
4	Casting of SCC	September 22, 2023	—
5	Testing of compressive strength and *E* modulus of 3DPC	October 12 to 13, 2023	28 to 29
6	Testing of compressive strength and *E* modulus of SCC	October 20, 2023	28
7	Testing of compressive strength of SCC	November 2, 2023	41
8	Transporting columns to RISE	October 24, 2023	32 and 62
9	Testing chloride ingress	October 31, 2023	69
10	Loading tests on columns	October 31 to November 3, 2023	39 to 42 and 69 to 72
11	Coring of columns	November 6 to 10, 2023	45 to 49 and 75 to 79
12	Pullout tests	November 13 and 15, 2023	52 to 54 and 82 to 84
13	Testing of compressive strength and *E* modulus of 3DPC	November 22 to 23, 2023	69 to 70
14	Freezing-and-thawing tests	November 9, 2023 to January 4, 2024	78 to 134
15	Carbonation tests	November 3, 2023 to January 12, 2024	72 to 142

*Dual ages or ranges correlate with SCC and 3DPC, respectively

Table 2:
Mixture proportions for the 3DPC and SCC

Ingredients	3DPC		SCC	
	kg/m³	lb/yd³	kg/m³	lb/yd³
Cement (CEM I*)	625	1053	—	—
Cement (CEM II/A-LL†)	—	—	325	548
Limestone filler	—	—	83	140
Water	312	526	195	329
Gravel (0 to 4 mm [0 to 0.16 in.])	1350	2275	—	—
Gravel (0 to 8 mm [0 to 0.32 in.])	—	—	1032	1739
Gravel (8 to 16 mm [0 to 0.64 in.])	—	—	685	1155
Air-entraining admixture	1.25	2	—	—
High-range water-reducing admixture	>0‡	—	4.45	—
Accelerating admixture	>0‡	—	—	—
Other chemicals	>0‡	—	—	—
Sum	2288	3857	2324	3917
w/c	0.5	—	0.6	—

*Contains 95% portland cement

†Contains >80% portland cement and <20% limestone filler

‡Brands and volumes are proprietary

cylinder compressive strength of 28 MPa [4060 psi]). Because the 3DPC had a lower water-cement ratio (*w/c*), it was anticipated that its strength would be 20% higher.

Loading Tests

The research project included performing loading tests on four composite and two homogeneous concrete columns (Fig. 1). The columns were 3 m (10 ft) tall and had a circular 300 mm (12 in.) diameter cross section. The composite columns consisted of a 40 mm (1.6 in.) thick 3DPC form that was filled with SCC. The homogeneous columns were cast with the same SCC. All columns were reinforced with four vertical 8 mm (0.3 in.) diameter bars and ten 5 mm (0.2 in.) diameter stirrups. Tested compressive strengths were 56 MPa and 44 MPa (8120 psi and 6380 psi) for the 3DPC and the SCC, respectively.

The columns were simply supported at both the top and bottom (Fig. 2). They were loaded by a centrally placed hydraulic load, which was increased continuously with 350 kN (78.7 kip) increments until failure. For the columns showing the highest failure load, the failure occurred after the sixth load increment at approximately 24 minutes.

In a previous study,[7] testing of concrete-filled steel pipe columns (without bond between the steel and the concrete) showed that only the steel pipe carried the load when the load was applied on the steel pipe only (no load on the concrete core). In our research, we wanted to check if there is a difference between SCC-filled 3DPC pipe columns for which the entire cross section is loaded (Group A, 300 mm [11.8 in.] loading diameter) and similar columns for which only the area of the SCC core is loaded (Group B, 200 mm [7.9 in.] loading diameter). Two composite columns and one homogeneous column were included in each group.

The results from the loading tests are summarized in Table 3. Based on our observations:

- For the columns loaded at the entire cross section (Group A), the load-carrying capacity of the composite columns was equal to that of the homogeneous column;
- For the columns where only a central part of the cross section was loaded (Group B), the composite columns also developed load-carrying capacity equal to that of the homogeneous column;
- Columns in Group B developed only 60% of the obtained load-carrying capacity of the columns in Group A;
- None of the columns developed a load-carrying capacity close to the predicted value of 3100 kN (697 kip), calculated as the area of the cross section times the measured compressive strength; and
- The failure mode was similar for all columns (Fig. 3), and the compressive failure appeared suddenly.

The laboratory report[8] provides a discussion on the third and fourth observations. The SCC strength in the narrow column cores might have been less than the one measured on the control cylinders, and there might have been an unintended eccentricity, despite the technicians' efforts to avoid it. The eccentricity is likely to be greater in Group B than in Group A, which gives a possible explanation for the third observation. The relatively low column slenderness, height-to-diameter ratio of 10, implies that buckling can be excluded as an explanation.

Fig. 1: 3DPC forms and a cardboard form prior to casting SCC. A rectangular 3DPC form is visible in the bottom left corner of the photo. This form was used for enabling coring of samples for subsequent durability tests

Fig. 2: The setup for the loading tests in the RISE laboratory in Borås, Sweden

The first and second observations are the most interesting ones, however. They show that the composite column was as strong as the homogeneous one, and they indicate a sufficient bond between the SCC core and the 3DPC form. This was also confirmed with pullout tests (taken from undamaged parts of the composite columns after the loading tests), which resulted in an average bond strength of 1.75 MPa (254 psi), considerably exceeding frequent values of the required bond strength of 1 MPa (145 psi), often used in Europe.

Durability Tests

At present, 3DPC has a small maximum aggregate size and a high cement paste content. Usually, the *w/c* is low, resulting in a high cement content but also a dense concrete, which generally provides good durability.

Table 3:
Ultimate loads and deformations

Group	Diameter of loading area, mm (in.)	Column No.	Column type	Ultimate load, kN (kip)	Deformation at ultimate load, mm (in.)
A	300 (12)	I	Composite	2240 (504)	6.8 (0.27)
		IV	Composite	2529 (508)	8.2 (0.33)
		V	Homogeneous	2074 (466)	14.7 (0.58)
B	200 (8)	II	Composite	1410 (317)	3.1 (0.12)
		III	Composite	1411 (317)	4.6 (0.18)
		VI	Homogeneous	1370 (308)	4.3 (0.17)

Fig. 3: Column No. III after failure

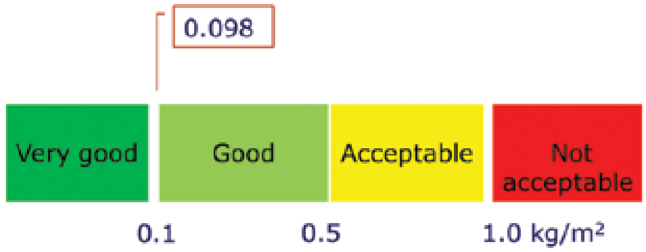

Fig. 4: Scaling mass after freezing-and-thawing tests per Swedish standard SS 137244:2019[9] classification (Note: 1 kg/m^2 = 0.21 lb/ft^2)

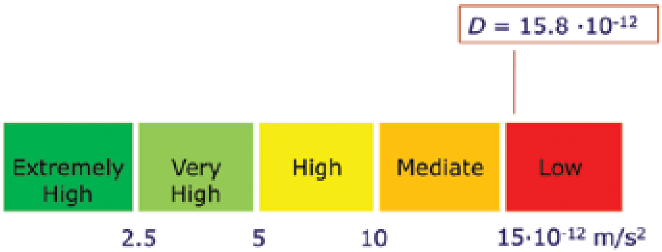

Fig. 5: Chloride migration coefficient *D* in relation to used classification (Note: 1 m^2/s = 10.76 ft^2/s)

In our research, the durability of the 3DPC form working as concrete cover for column reinforcement was investigated through freezing-and-thawing tests and resistance to carbonation and chloride migration evaluation. The freezing-and-thawing tests were carried out according to the Swedish standard SS 137244:2019,[9] requiring 56, 24-hour cycles between +20 and −20°C (+68 and −4°F). The accumulated volume of scaled mass was measured after 7, 14, 28, 41, and 56 days. The results demonstrated "good frost resistance" on the border of "very good frost resistance" according to that standard (refer to Fig. 4).

The resistance to carbonation was evaluated according to the Swedish and European Standard SS-EN 12390-12:2020.[10] The carbonation depth was measured after 7, 28, and 70 days. This test is an accelerated test because the carbonation depth is measured in a chamber having a carbon dioxide (CO_2) concentration of 3%, roughly 70 times higher than in the current atmosphere (415 ppm = 0.04%). However, this test method has been shown to rank concrete mixtures correctly.[11] In our studies, a carbonation depth of 4.6 mm (0.18 in.) was measured after 70 days. This value is slightly lower than the ones of 6 to 12 mm (0.25 to 0.5 in.) recently measured by Heidelberg Materials Betong Sverige and RISE for concrete mixtures with the same cement type and a w/c = 0.5 to 0.6.[8]

The resistance to chloride migration was measured according to the Nordtest method NT Build 492.[12] This is also an accelerated test method where the chloride ingress depth is measured on test specimens subjected to a 10% NaCl solution. The method includes the calculation of chloride migration coefficient D, using the inverse error function to solve Fick's second law. The obtained mean value for three tested specimens was 15.8×10^{-12} m^2/s (1.7×10^{-10} ft^2/s). NT Build 492 does not provide any interpretation of the results. Instead, the obtained value may be compared with values found in the literature.[13] The result of the testing was determined to fall between the worst ("Low") and the second-worst class ("Mediate") on a five-grade scale (refer to Fig. 5).

The limited resistance to chloride migration might be attributed to the variation in the thickness of the printed form layers (thickest in the middle of a printed layer and thinnest between two layers), as well as the porosity of the interlayer between two layers, which is higher than that of an individual layer.

Concluding Remarks

The technology of composite concrete columns with permanent 3DPC forms filled with SCC is promising. The columns developed load-carrying capacities corresponding to homogeneous ones. Pullout tests showed that it is possible to develop a bond strength exceeding 1 MPa (145 psi) between the 3DCP form and the SCC.

Many current 3-D concrete printers are provided with nozzles that cannot handle concrete mixtures with large aggregate particles. That means that the "ink" contains a lot of cement. However, if the cement-rich 3DPC can be combined with an SCC with a low cement content, it will still be possible to reach sustainability goals.

The idea behind the durability testing part of this research was to evaluate a dense 3DPC form working as cover for the reinforcement inside the SCC core of the column. The test results indicated that the 3DCP form is frost-resistant and has a good resistance to carbonation. The remaining issue is the resistance to chloride ingress. At this stage, the composite columns cannot be used in marine applications or in cases where deicing salts are present. The interlayer between two printed layers may be responsible for insufficient resistance to chloride migration. Impregnation with a hydrophobic agent—for example, silane or siloxane—may be a possible solution. Further research and development of the concrete mixture and the printing process may solve this problem.

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Selected for reader interest by the editors.

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