Cellular Sprayed Concrete

An innovative method for remixing and making high-performance shotcrete

By Kyong-Ku Yun

Cellular sprayed concrete is an innovative method of remixing ordinary portland cement (OPC) concrete into a high-performance concrete (HPC) by adding cellular material and silica fume or other powdered admixtures at a jobsite. This method enables the distribution of very-fine silica fume or other powdered admixtures in stiff ready mixed concrete.

Creating cellular sprayed concrete is a simple and economical way to produce HPC that can be shotcreted or conventionally placed at a jobsite. It can be applied to many jobs, including new construction, major rehabilitation work, underground applications, and architectural projects.

This article discusses the concept of cellular concrete, its fresh properties, hardened properties, durability, validation of silica fume dispersion, and also provides examples of field applications.

INTRODUCTION

HPC is produced by incorporating silica fume or other powdered admixtures (mineral or organic) in the concrete mixture. The powdered materials are usually preblended in a factory. Because of their fineness, it is very difficult to add and disperse them in a batch plant when the concrete is mixed. One can use preblended cement to produce HPC, but it may need extra attention for all batching and delivery procedures, including blending, packing, transportation, stocking, and mixing. This extra work can result in very expensive concrete.

Silica fume is a by-product of ferrosilicon or silicon metal; it has nanoparticles. It also has a micro filling effect and pozzolanic reaction that helps to fill the voids between the hardened cement particles, resulting in reduced permeability, increased watertightness, higher strength, and ultimately more durability.[1] Silica fume is a popular material for shotcrete work because of its improved adhesion, increased layer thickness, as well as higher strength and durability. With silica fume's high fineness, it is commonly preblended with cement, and this can lead to a higher cost.

Fig. 1: (a) Cellular material; and (b) spraying cellular sprayed concrete

THE CONCEPT AND INNOVATION OF CELLULAR SPRAYED CONCRETE

Fresh concrete is generally a flowable material but with low fluidity. When silica fume is added to fresh concrete, it will not be well dispersed due to its high fineness and large effective surface area. Cellular material embeds air content (Fig. 1(a)), which has a ball bearing effect and enlarges concrete's volume when added to concrete. If a large amount of cellular material—for example, 30% by volume—is added to fresh concrete, it will increase the concrete's fluidity. If silica fume is added to the modified cellular concrete with high fluidity, it can be easily dispersed in the much more liquid concrete.[2] Concrete with the cellular material traps a lot of air inside, which reduces the compressive strength of concrete. However, this much higher air content can be substantially reduced by spraying the concrete with the high velocity inherent in the shotcrete process (Fig. 1(b)).

Production cost and construction time can be reduced because the high-performance cellular sprayed concrete is produced at the jobsite with only the cost of adding silica fume and cellular material. Mixing the cellular concrete on the jobsite eliminates the need for production, transportation, and storage costs when using special blended cement.[3]

The cellular sprayed concrete process includes:

1. Transportation of ordinary low-slump ready mixed concrete to a jobsite in a truck;
2. Then, 20 to 30% by volume of preformed cellular material is discharged into the truck, transforming the stiff concrete, into a slurry with very high slump;
3. Silica fume is added and the concrete is remixed to disperse the silica fume; however, the concrete still contains lots of air; and
4. The cellular concrete with the high volume of air is discharged into the concrete pump and sprayed from the nozzle at the end of the delivery line with high velocity. The impact force of the sprayed concrete process reduces the air content, creating low-slump HPC in place.

Table 1: Mixture Design

	w/cm	*s/a* (%)	Unit weight (kg/m^3)					
			w	c	FA (S)	CA (G)	SF	Air entrainment
OPC	0.4	75	184	460	1111	376	—	1.8
SF6	0.4	75	184	432	1065	361	28	2.3
SF8	0.4	75	184	423	1050	355	37	2.3
SF10	0.4	75	184	414	1035	350	46	2.3

Note: *s* is fine aggregate (sand); *a* is total aggregate (sand and gravel)

Slump and Air Content of Cellular Sprayed Concrete

Slump was checked using ASTM C143/C143M at various stages: as delivered to the site, after adding cellular material, after adding silica fume, and after spraying. Air content at each stage was measured based on ASTM C231/C231M for air content up to 10% of air content, and using the unit weight method for air content above 10%. The OPC concrete was very stiff, with 10 mm (0.4 in.) slump, but became fluid by adding 27% cellular and then became stiff concrete with 50 mm (2 in.) slump after spraying. The air content in the ready mix concrete was 3.5%, then increased to 27% after adding cellular, 24% after adding silica fume, and returned back to 4.5% after spraying. The spraying broke down the big air bubbles by impact.

Dispersion Theory of Silica Fume in Cellular Sprayed Concrete

The ultra-fine particles of silica fume cannot be dispersed in fresh, relatively stiff concrete; however, it can be mixed in a fluidized concrete (slurry). Silica fume is dispersed in cellular sprayed concrete in three ways: mixing more easily in the more fluid slurry; increasing the concrete volume for a larger contact area;[4] and additional mixing provided by the impact and resulting agitation from high velocity spraying.

Black carbon is 10 times finer than silica fume and was used in the trials of cellular sprayed concrete to analyze the dispersion effect. The dispersion of silica fume was verified by energy dispersive X-ray spectroscopy (EDS) analysis, where the distribution of the components of cellular sprayed concrete was analyzed with the standard deviation and coefficient of variation of the silicon (Si) content at each point.[5]

EXPERIMENTAL PROGRAM AND TEST RESULTS

Mixture Design and Tests

The basic concrete mixture design was set to have 460 kg/m^3 (775 lb/ft^3) of cement content, a water-cementitious materials ratio (*w/cm*) of 0.4, and 75% of fine aggregate ratio (*s/a*). An air-entraining agent was used to achieve the targeted slump of 80 ± 20 mm (3 ± 0.8 in). The main experimental variable was the amount of cellular material used by volume. Cellular amounts of 15, 20, 30, and 35% were used. The effect on concrete properties was investigated by measuring slump, air content, compressive strength, and an air void image analysis.

The OPC used in this test has a fineness of 3300 cm^2/g and specific gravity of 3.15. The maximum size of coarse aggregate was 10 mm (3/8 in.), which has a specific gravity of 2.67. The silica fume has a specific surface area of 200,000 cm^2/g. The foaming agent has surface-active molecules and is composed of hydrophilic groups and hydrophobic groups that changed the characteristics of the surface tension of a diluted aqueous solution in the foaming agent, and thus the viscosity.

Air Content and Slump Test Results

The change in air content and slump was measured, compared, and analyzed in accordance with the cellular amount variations of 15%, 20%, 30%, and 35%. Very high air content was measured before spraying, but it was reduced to 4 to 6% after spraying regardless of initial air content. This is an indication of dispersing big air bubbles, leaving only small ones inside the cement paste. The increased air content before spraying resulted from the incorporated foam, and was dissipated after spraying to ultimately keep a relatively constant amount of air in the in-place concrete.

Figure 2 illustrates the test results of slump variations before and after spraying. Due to the ball bearing effect, higher slump was measured as the amount of cellular incorporated increased. However, slump measured after spraying was reduced to less than 50 mm. It had very low slump after spraying, which is good for stability of the placed concrete.

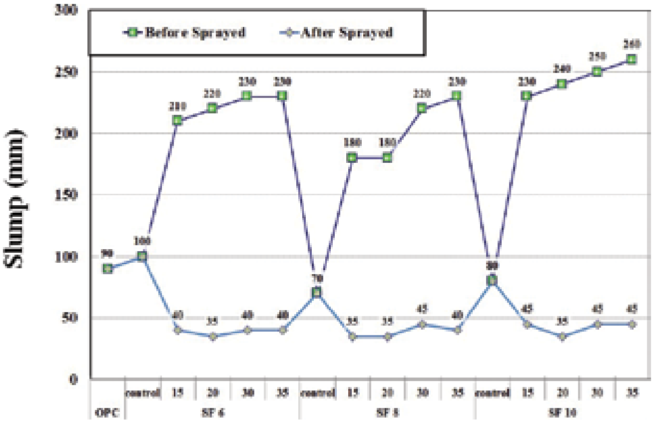

Fig. 2: Slump measured before and after spraying

Compressive Strength Test Results

To investigate the variations in compressive strength according to the amount of cellular incorporated, compressive strength was measured at 28 and 56 days. Compressive strength at 28 days showed a tendency to generally decrease as the amount of cellular increased, as shown in Fig. 3. Increased water content was at fault, due to effectiveness in focusing only on the cellular content's dispersing of the silica fume and neglecting the amount of water included in the cellular material.[6]

Spacing Factor and Specific Surface Area Test Results

Figure 4 shows the results of air void image analysis for the test specimen after spraying. There is a tendency for spacing factors to decrease as the cellular amount increases, and vice versa for a specific surface area. These are good indications that the freezing-and-thawing resistance of cellular sprayed concrete is acceptable for harsh cold weather environments.

EXAMPLES OF FIELD APPLICATIONS

Regionally Symbolic Tunnel Portal

Tunnel portals were built using the sprayed concrete (shotcrete) process that allowed carving for texture and acid staining for coloring, thereby creating an appearance of rock. These tunnel portals were designed with the input of the local community to portray their regional character. The local communities were very satisfied to have their own beautiful and symbolic tunnel portals. This was made possible with the inherent benefits of shotcrete technology such as adaption to curved and irregular surfaces, different surface finishes, excellent hardened physical properties, reduced construction time, and cost effectiveness.[7]

The construction period was shortened by adopting cellular sprayed concrete because it provided a massive quantity of concrete using conventional ready-mix concrete and wet-mix shotcrete equipment. The additional equipment required for making cellular concrete included a foam generator and a nozzle. This maximized the cost savings for HPC by minimizing the special equipment required. Figure 5 shows an example of a tunnel portal built with cellular sprayed concrete.

Artificial Rock Slope Stabilization

Spraying, carving, and coloring natural rock patterns is an eco-friendly technology that harmonizes with the surrounding landscape. This method was adopted for stabilizing adjacent slopes. It was designed with the input of the local government officials who were pleased with the beautiful, eco-friendly slope. Spraying, carving, and coloring were done according to the given specifications.[8]

A high placement rate of HPC was possible in the first lift by shooting with the optimized cellular technique. After shooting the second lift, the exposed surface of fresh concrete was carved into natural rock patterns with added coloring. This technique helped to match the natural rock shapes and colors, as shown in Fig. 6.

Two-Lift Concrete Pavement (2LCP)

Two-lift concrete paving involves placing two layers of concrete *wet-on-wet* instead of the traditional method of using a single homogeneous layer of concrete. The thick bottom layer provides the opportunity to optimize the use of local aggregates and recycled materials to produce an economical, durable mixture, and then places the top high-quality pavement system with the most desirable surface characteristics, such as improved skid resistance and reduced noise. The time gap between placing the layers is often no more than 30 minutes. The challenge involved in the construction of two-lift concrete systems might be the additional cost and logistics required for two concrete batch plants to produce different concrete mixtures and two slip-form pavers for paving both the bottom and top layer at the same time.[9]

In this application for cellular sprayed concrete, it attains its high performance with the addition of silica fume and polymer powder. The cellular material makes it suitable for spraying while maximizing the dispersibility of the fine powders. The spraying process regulates the consistency

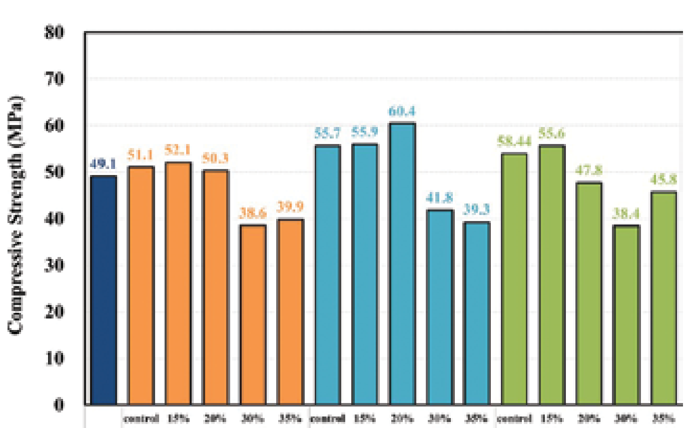

Fig. 3: Compressive strength after spraying at 28 days

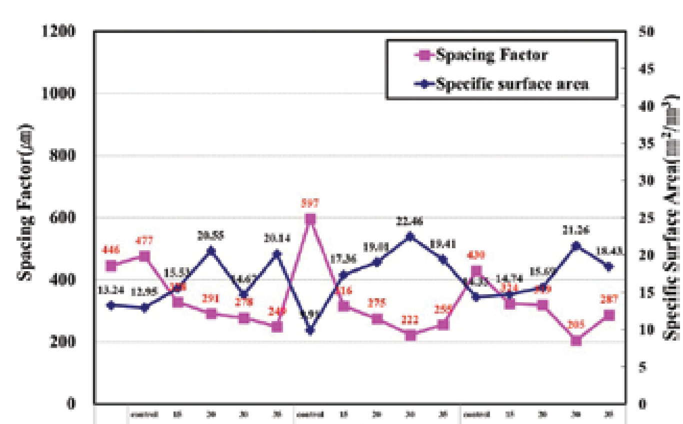

Fig. 4: Image analysis of air void spacing

Fig. 5: Regionally symbolic tunnel portal built with cellular sprayed concrete

Fig. 6: Artificial rock slope stabilization with cellular sprayed concrete

of the mixture by dissipating the increased air content due to the addition of cellular material.[10]

Cellular sprayed concrete can be adopted in the construction of two-lift concrete pavement by supplying conventional concrete to a site where it will be remixed on site to achieve HPC. There are future plans to conduct trials to develop a simple and economical field application of 2LCP with only conventional concrete supply.

Conclusions

Cellular sprayed concrete is a new concept. It is produced by incorporating cellular material and mineral admixtures into conventional concrete at a jobsite. This method allows for a reduction in production costs and construction time as high-performance cellular sprayed shotcrete is produced with ready mix concrete on a jobsite without the production, transportation, and storage required when a special blended cement is used.

Cellular sprayed concrete is very simple, economical, unique, and versatile. This innovative method of transforming cellular sprayed concrete was successfully adopted at tunnel portal slope stabilization and 2LCP.

References

1. Wolsiefer, J., and Morgan, D.R., "Silica Fume in Shotcrete," *Concrete International*, V. 15, No. 4, Apr. 1993, pp. 34-39.

2. Han, S.-Y., "Dispersion of Silica Fume by Air Slurry and its Effect on Mechanical Properties at Ready Mixed Concrete," MS dissertation, Kangwon National University, Korea, 2014.

3. Yun, K.-K.; Han, S.-Y.; Lee, K.-R.; and Namkung, K., "Cellular Sprayed Concrete for Simple and Economical Remixing," *Shotcrete for Underground Support XIII*, Münster, Germany, 2017.

4. Kim, D.-A., "Dispersibility of Silica Fume in Cellular Sprayed Concrete for Simple and Economic 2LCP," MS dissertation, Kangwon National University, Korea, 2016.

5. Yun, K.-K.; Kim, D.A.; and Namkung, K., "Dispersibility of Silica Fume in Cellular Sprayed Concrete for Simple and Economic Two-Lift Concrete Pavement," 11th International Conference on Concrete Pavements, San Antonio, TX, 2016.

6. Jo, J.-W., "Variation of Water-Cement Ratio in Cellular Sprayed Concrete for Two-Lift Concrete Pavement," MS dissertation, Kangwon National University, Korea, 2016.

7. Yun, K.-K.; Kim, Y.-G.; and Choi, S.-Y., "Regionally Symbolic Tunnel Portals at Expressway," *Shotcrete*, V. 20, No. 2, Spring 2018, pp. 16-18.

8. Yun, K.-K.; Lee, K.-R.; Choi, S.-Y.; and Kim, Y.-G., "Application Examples of a Very Economical Way of Cellular Sprayed Concrete on Retaining Wall and Artificial Rock," *Shotcrete for Underground Support XIII*, Münster, Germany, 2017.

9. Namkung, K., "A Study on the Two Lift Concrete Pavement Using Cellular Sprayed Concrete," PhD dissertation, Kangwon National University, Korea, 2017.

10. Yun, B.-R., "Shrinkage Cracking Resistance of a Very High Perfomance Cellular Sprayed Concrete for 2LCP in Accordance with Polymer Powder Mixing Rate," MS dissertation, Kangwon National University, Korea, 2017.

Kyong-Ku Yun *is a Professor at Kangwon National University, Chuncheon-si, Gangwon-do, South Korea. He received his PhD from Michigan State University, East Lansing, MI, in 1995. His research interests include shotcrete and concrete materials. Recently, he has been heavily involved in shotcrete research and has consulted on the shotcrete material and overall procedures for this rehabilitation project.*