Development of Durable Dry-Mix Shotcrete in Quebec

by Daniel Vézina

Shotcrete has been widely used by the Ministère des Transports du Québec (Quebec D.O.T.) for restoration and rehabilitation of concrete structures since the mid-1960s. Throughout the years, this technique has been used at an increasing rate and has followed advances in shotcrete technology. These advances included improvements in material and mixture designs, development of durable materials with regard to frost action, bond improvements, and the use of set accelerators compatible with durability requirements.

Development of a Durable Shotcrete Mixture for Cold Weather Climates

Initially, our first document concerning shotcrete was a 1965 specification for "gunite" (that is, a sand/cement/water mixture applied by the dry-mix shotcrete process). This specification was used until 1975 when the use of "gunite" as repair material was abandoned. At that time, structural inspections revealed poor in-place performance, mainly related to severe cracking, debonding of patch material, and deterioration caused by freezing and thawing.

In the mid-1980s, a large number of highway structures, particularly major structures in the Montreal area, needed to be repaired. Everyone knew shotcrete would be a practical and economical solution if a durable mixture was used and suitable construction methods and practices were implemented.

Figure 1. Preparation for shotcrete repair; Metropolitan Blvd., Montreal, Canada.

Many experiments took place during the period from 1984 to 1990 to improve upon the quality and performance of the old "gunite" mixtures. The use of blended cement (Type I cement with 8% silica fume) was the first modification of the mix design. In combination with better surface preparation techniques (*ASA Magazine*, V.1, No.2, May 1999), the bonding of the shotcrete to existing concrete was greatly improved. Using silica-fume-blended cement decreased the total content of cement of the mixture, improved strength, decreased the water absorption and volume of permeable voids, and also had a great beneficial effect on chloride permeability (values below 1500 Coulombs). Laboratory tests conducted on this silica-fume-modified material indicated many improvements, but unfortunately, frost durability, (surface scaling resistance and resistance to damage from rapid freezing and thawing) was still problematic.

From 1985 to 1989, numerous tests were conducted during various projects at Quebec D.O.T. to evaluate the feasibility and effect of introducing air-entraining admixture into dry-mix shotcrete. A summary on the evolution of the mixture design is given in Table 1. The purpose of these studies was to entrain a large amount of small air bubbles in the dry-mix shotcrete, and thus lower the spacing factor to meet the severe durability acceptance criteria established by the Quebec D.O.T. In these tests, the material was delivered to the job site in a concrete mobile volumetric batcher and the air-entraining admixture was added to the water in the reservoir connected to the nozzle. The results obtained on specimens taken from 10 different contract locations indicated that with a dosage of 1 to 2 L/m^3 of air-entraining admixture, *in-place* plastic air content varied between 3.5 to 6.0%, and the spacing factor varied between 140 to 400 microns. The spacing factor for mixtures shot without the air-entraining admixture was between 400 and 700 microns. Rapid freezing-and-thawing tests (ASTM C 666) and deicer salt scaling tests (ASTM C 672)

Table 1. Mixture design evolution for dry-mix shotcrete in the Province of Quebec

	1965-1984	1985-1995
Cement (kg/m³)	525	450 (SF)
C:S, vol	1:4	1:3,2-4,5
Coarse aggregate 10-2.5 (kg)	—	235
Polypropylene fiber (kg/m³)	—	1
Air-entraining admixture (L/m³)*	—	1-2
Set accelerator	Authorized	Specified product

**Powdered air-entraining admixture for prebagged shotcrete.*

Table 2. Standard Quebec D.O.T. dry-mix shotcrete

Cement (10SF)*	450 kg/m³
Fine aggregate	1510 kg/m³
Coarse aggregate 10-2.5 mm	235 kg/m³
Polypropylene fibers	1.0 kg/m³
Air-entraining admixture	1 to 2 L/m³ (approximately 150ml/L of shooting water)

1 kg/m³ = 1.7 lbs/yd³
1 L/m³ = .2 gal/yd³
**The type 10SF contains about 8% silica fume.*

allowed us to conclude that shotcretes with a spacing factor lower than 300 microns should exhibit good durability.

While durability was improved by the addition of an air-entraining admixture, the application technique was not without problems. Some of the problems encountered, along with probable causes, were as follows:

- Excessive cracking, caused by:
  - High cement content
  - Sand too fine, requiring excessive water
  - Poor curing of fresh shotcrete in hot and windy conditions
  - No prewetting of concrete substrate
  - Shotcrete repair thickness less than 40 mm
  - Zones delineating repair of irregular shapes.
- Excessive shrinkage caused by
  - Lack of proper curing
  - Shotcreting in hot and windy conditions
  - High cement content

In 1989, the mixture design used for dry process shotcrete was modified to remedy the deficiencies encountered, and the standard Quebec D.O.T. dry-mix shotcrete was developed. It was used for major repairs in 1990 ($80M) on Highway 40 (Metropolitain Boulevard), the main expressway that runs through the center of Montreal, Canada. This 10 km long elevated expressway had shotcrete repairs made on its underside, as well as on over 5000 columns. The introduction of 10% (dry mass) of 10 mm maximum size coarse aggregate and the addition of 1 kg/m³ of polypropylene fiber were the main modifications to the mixture design (Table 2). In addition to these mixture improvements, careful surface preparation and good curing practices were implemented. After 10 years of severe exposure to weather and service, including deicing salts, the shotcrete repairs are performing very well. Typical physical properties of this shotcrete are illustrated in Table 3.

The standard mixture design has now been used since 1990 for bridge repairs in the Province of Quebec. In 1994, a new research program, in cooperation with Laval University and industrial partners, was initiated. The objective was to develop and optimize materials and an application

Figure 2. Finishing operation on column after shotcrete application.

Figure 3: Curing of repaired columns, note the wet burlap covered by plastic.

technique for shotcrete as a repair material. An example of some of the research conducted so far has been the development of a pre-bagged dry-mix shotcrete that incorporates a dry-powdered air-entraining admixture, polypropylene fibers, and in some cases, a set accelerator (currently in use by the Quebec D.O.T.). This research effort has demonstrated that some types of set accelerator can have detrimental effects on frost durability, which has led to a restricted use of these products.

Table 3: Typical mechanical properties for standard Quebec D.O.T. dry-mix shotcrete

	Typical results
Strength 7 days	30 MPa
28 days	40 MPa
Water absorption (ASTM C 642)	4.5%
Volume of permeable voids (ASTM C 642)	10.2%
Air content (as shot)	4.5%
Spacing factor (µm)	100-150 µm
Chloride permeability (ASTM C 1112)	1150 Coulombs
Scaling resistance (ASTM C 672)	0.4 kg/m²

1 MPa = 145 psi

Conclusions

The development of durable dry-mix shotcrete repairs contributes to an increase in the structural service life of bridges. Although high dosages of admixture are required, it has been demonstrated that it is possible to entrain an adequate air void system in dry-mix shotcrete. Air-entraining admixtures have been used for more than 10 years in Quebec. Field surveys and laboratory tests confirm that air entrainment is necessary to ensure adequate freezing-and-thawing durability of dry-mix shotcrete in the exposure environment to which bridges are subjected in Quebec.

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