Shotcrete Research and Development at Laval University

By Marc Jolin

The last 25 years have seen many exciting innovations in the field of shotcrete, primarily involving improved equipment, novel mixture designs, and new concrete chemical admixtures. The use of dry-mix shotcrete for ground support in mining has increased exponentially, and applications of wet-mix shotcrete have expanded to include tunnels, ground support, new structures, rehabilitation, and more. This success can be directly attributed to these innovations—through the quality of the shotcrete produced, the increased robustness and flexibility of the methods, and the greater variety of applications currently possible. Of course, all this has generated heightened expectations and increasingly stringent requirements for shotcrete in terms of durability, quality control, and mixture design characteristics.

It is well known that quality shotcrete requires a combination of adequate airflow velocity, proper material proportions, and appropriate nozzle handling. On top of all the basic concrete technology notions, high-velocity pneumatic application of concrete brings about new concerns: material losses through rebound or fallouts; buildup thickness; and compaction and encapsulation of reinforcement. Many factors related to the shooting parameters (such as process, air velocity, shooting angle, orientation, and thickness of shooting) and mixture design parameters (including cement content, silica fume content, water content, and aggregate gradation) impact shotcrete placement—all of which are simply research topics waiting to be explored.

Since 1997, the Shotcrete Laboratory at Laval University has been actively involved in education and research and development in shotcrete. This article presents a small sample of the key results and applications emerging from these research efforts on both dry- and wet-mix shotcretes to illustrate the importance given to the placement process in our research.

WET-MIX SHOTCRETE

The placement of high-strength wet-mix shotcrete is sometimes complicated by the compromise required between pumpability and shootability. At the pump, a relatively fluid, easily pumped concrete is required, whereas at the nozzle, a stiff material that neither sags nor sloughs when shot on the wall is desired. A solution to tackle this apparent paradox was put forward by Denis Beaupré in the course of his research work at the University of British Columbia,[1] and is often called the Temporary High Initial Air Content.[2] The approach is simple and very clever, whereby fresh concrete's fluidity is increased to meet pumpability requirements by introducing large amounts of entrained air bubbles instead of relying solely on water reducers and plasticizers (10 to 15% air content prior to pumping). The beauty of it is that during shooting, large amounts of air are lost upon impact and compaction; reduced workability is instantaneously obtained as shotcrete hits the receiving surface, thus improving the shootability of the shotcrete. Air loss upon impact is known as the "slump killing" effect.

Although this concept has seen many early users in the industry and is now used around the globe, it was only later that a clear understanding of the mechanisms behind the improved pumpability was brought to light by Jolin et al.[3] When trying to understand exactly what happens in the delivery hoses, Jolin et al. found that all the air bubbles were easily dissolved into the cement paste under the normal operating pressures found in concrete pumping. Through pumping a dozen different wet-mix concretes, it was found that the capacity to pump or not had apparently little to do with the mixture design (Table 1). Indeed, only small modification of the total paste content for a given mixture design would make it pumpable. Considering that the relative proportion of aggregates and the water-binder (*w/b*) ratio were both maintained constant, it is difficult, looking at the first columns of Table 1, to understand the key parameters that made a mixture pumpable or not. (Note: all mixtures would pump in a 2 in. [50 mm] internal diameter hose; the challenge in this study was going down to a smaller 1.5 in. [38 mm] internal diameter hose.)

A careful examination of the results reported in Table 1, as well as a comprehensive analysis of the laboratory observation and available literature, led the authors to derive what is called the Real Paste Content (last column of Table 1, complete calculation method in Jolin et al.[3]), defined as the "amount of paste (%) present in the concrete while under pressure." Therefore, it is a volumetric interpretation of the paste content when the material is under pressure.

Table 1: Experimental results of pumpability test

Mixture[*]	Binder content lb/yd^3 (kg/m^3)	Air content (before pumping), %	Pumpability	Real paste content[†]
A	661 (392)	13	NO	33.2
A-*mod1*	683 (405)	13	*Blocked-2 strokes*	34.2
A-*mod2*	700 (415)	13	Pumpable	35.1
B	684 (406)	7	NO	31.8
B-*mod*	750 (445)	7	Pumpable	35.1
C	738 (438)	3	NO	33.1
C-*mod*	784 (465)	3	Pumpable	35.1
C	679 (403)	13	NO	33.8
C-*mod*	708 (420)	13	Pumpable	35.2
D	674 (400)	13	NO	33.8
D-*mod*	700 (415)	13	Pumpable	35.1

[*] All water-binder ratios are 0.41; slump for all mixtures is 75 to 100 mm (3 to 4 in.)

[†] Volume of paste in the concrete under pressure

It is interesting to note that the paste volume changes as pressure is applied to the concrete because the dissolving air volume diminishes to negligible values. Therefore, as pressure increases, the paste content becomes equivalent to the volume of binder material and water.

As it can be seen, it appears that a value of real paste content of 35.1% is somewhat a minimum value below which a mixture is not pumpable (with the particular aggregates used and a 1.5 in. [38 mm] internal diameter hose). The implications of this finding are significant; it not only shows (again) the importance of providing a sufficient amount of paste to coat all the aggregates and lubricate the inner wall of the delivery hoses, but it more interestingly demonstrates that there is a threshold value for the real paste content below which pumping is impossible. Combined with previous research, we can further affirm that this threshold value will change with the aggregate gradation and the hose diameter.[4,5] The real paste content calculated by Jolin et al. is the first time we have an actual value and a calculation method to start optimizing our mixture design for pumping and better select our aggregates size and proportions.

SERVICE LIFE PREDICTION

Service life prediction is one of the most recent and important topics considered in the Shotcrete Laboratory at Laval University. The service life modeling tool called STADIUM® was adopted both for its capacity to accept varying types of concrete and its capability to include numerous types of transport mechanisms in modeling the concrete's performance.[6] Service life modeling is an invaluable tool for owners and engineers, as it considers the transport mechanisms of deleterious substances in the concrete porous network based on exposure conditions. The driving force behind each mechanism is quite straight forward: pressure, relative humidity and concentration gradient, and capillary suction. They can all act at the same time (in the same direction, independently, or even one against another) when considering contaminant ingress into concrete (for example, ingress of salt water and oxygen to initiate corrosion in a tidal zone for a concrete column). By considering time-dependent environmental conditions and transport properties, a service life modeling tool provides realistic estimates of the progression of concrete degradation and reinforcing steel corrosion. Thus, it can yield much more information on durability than possible with more conventional tests such as the measurement of porosity (ASTM C642) or of chloride penetration (ASTM C1202 or C1543).

Using the STADIUM simulation tool in the case study of a concrete dry-dock exposed to seawater, it was found that all the shotcrete tested was predicted to have better durability than an equivalent cast-in-place concrete. The most important conclusion to be drawn (Bolduc et al.[7]) is that the high-velocity pneumatic placement process that defines sprayed concrete plays a significant and positive role on the quality of the in-place concrete. Recent rather comprehensive research projects by Zhang et al.[8] as well as another from Power[9] support this statement; similar concrete mixtures always behaved better in the long term when they are sprayed as opposed to being cast-in-place.

SHOTCRETE PLACEMENT—ENCAPSULATION QUALITY

Proper reinforcement encapsulation is a concern among structural engineers, as there are limited specific guidelines for designers using shotcrete. Imperfections behind reinforcing bars (or any other obstacles) are reported in cases of excessive use of set-accelerating admixtures or with unskilled nozzlemen. To evaluate these concerns, past research has mainly focused on optimal mixture consistencies and best nozzle handling techniques to obtain perfect encapsulation.[10,11] Although these approaches have limited the creation of imperfections behind reinforcement by improving the rheology of the mixtures, the main issue has remained unresolved for decades: what is the influence of the size and distribution of voids on structural performance?

Unfortunately, the reliability and applicability of various encapsulation quality evaluation systems has been subject to ongoing debate from industry experts who have emphasized that evaluating the impact of a void's size on the bond strength of bars to concrete would be more useful. Early studies confirmed the assumption that small scattered voids would not have a considerable negative effect. However, a tool for the design and evaluation of shotcrete structures had yet to be offered. Thus, an extensive experimental investigation in which complex bond test specimens were built with different qualities of reinforcing bar encapsulation was undertaken to determine the impact of void geometry on bond performance of the bars by evaluating the slope of the load-slip curve, ultimate load, and failure mode. Part of the research created artificial voids encased with a cast-in-place shotcrete mixture to precisely establish their geometry and location.

Preliminary results have confirmed that a void with an unbonded perimeter of approximately 20% (refer to Fig. 1) of the bar's perimeter sets the limit at which bond strength begins to decrease drastically as initially hinted in a previous study.[12] Beyond that 20% unbonded perimeter limit, a change from a splitting failure mode to a pullout mode seems to be favored. Comparing sprayed and cast-in-place specimens, it was found that the slope of the load-slip curve was always stiffer for shotcreted specimens when the optimal airflow velocity was used. Further analyses will help engineers reliably assess the bond strength of reinforcing bars by the visual examination of cores and determine if corrective design measures are required.

Fig. 1: 20% unbonded perimeter (artificial void)

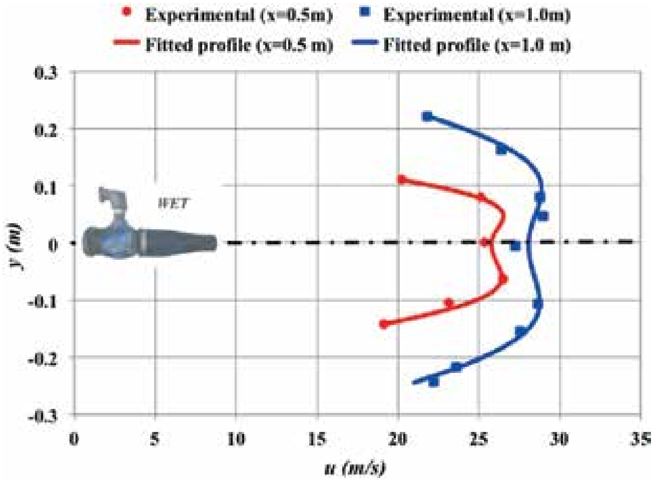

Fig. 2: Experimental and fitted velocity profiles u(y) obtained at 1.6 and 3.3 ft (0.5 and 1.0 m) from the wet-mix nozzle outlet

SHOTCRETE PLACEMENT—SPRAY

Further development of knowledge on shotcrete greatly depends on our comprehension of the material placement process, particularly for the reduction of rebound and control of the in-place material compaction and composition. Despite considerable advances in concrete mixture design for shotcreting in past decades, many aspects of the placement process are still not clearly understood.

Most of our understanding on the rebound phenomenon today relies on the work of Armelin and Banthia,[13,14] who were successful in modeling the different impact phases for a single aggregate on a fresh concrete substrate. Their work has allowed for demonstrating the key role of the energy (mass and velocity) of the incoming particles on the amount of rebound. Further investigation of the placement process was required—from the concrete transport in the hose and the shotcrete spraying at the nozzle to the study of the material impact on the surface. This reflection led to the development of a novel research approach using a high-speed camera, a project led by Ginouse (and Jolin) during his thesis.[15,16] Amongst the numerous innovative testing methods and significant results presented in his work, two of the most interesting ones can be seen in Fig. 2 and 3.

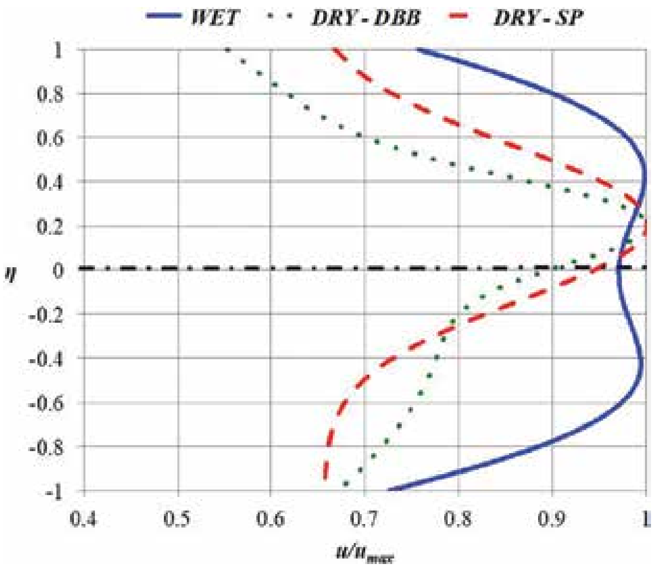

Fig. 3: Normalized axial velocity profiles obtained for the three shotcrete nozzles considered

In Fig. 2, the material velocity of a wet-mix shotcrete spray is followed as it exits the nozzle and values are reported for two positions: at 1.6 and 3.3 ft (0.5 and 1.0 m) for the exit of the nozzle. Obviously, the spray pattern widens as the distance from the nozzle increases, but what is noteworthy is the fact that the material accelerates between the 1.6 and the 3.3 ft (0.5 and 1.0 m) markers. In other words, the effect of the compressed air added at the nozzle has an important role even outside the nozzle as it keeps pushing the material forward.

Figure 3 reports the velocity profiles obtained 3.3 ft (1.0 m) for three different nozzles (one wet and two dry). For comparison purposes, the profiles have been normalized. What stands out in Fig. 3 is the differences in the shape of the profiles between dry- and wet-mix nozzles. With the wet-mix, the shape suggests that most of the particles travel at similar velocities, whereas the dry-mix nozzles show a rapid decrease of velocity as we move away from the middle of the spray axis. Keeping in mind the importance of the velocity (energy) of the particles as they hit the surface for control of rebound, the curves in Fig. 3 somewhat intuitively explain the higher amount of rebound found in dry-mix shotcrete where a smaller number of particles are traveling at the right velocity to minimize rebound when compared to wet-mix.

These two figures are only a small example of what this study allowed us to do. Further advances have since taken place: different wet-mix nozzle designs were compared to identify key parameters controlling velocity and rebound, and improved nozzle designs for dry-mix have been explored to better control the velocity profiles.

CONCLUSIONS

This article offers a brief glimpse of a large amount of information available in what can be a complex field. The author hopes that some of the information provided in this paper will support and promote more projects involving the use of shotcrete over conventional concrete. Such projects will only be feasible if the material (concrete) and placement method (spraying) are well understood by the specifier, designer, and contractor. Mistakes can be avoided by increasing the robustness of key components of the process and by adequately training crews, especially the nozzlemen who perform the job.

Acknowledgments

An article like this one would not be complete without acknowledging the contribution, through great efforts and hard work, of numerous students to these and many other projects. If you have ever held a nozzle in your hand or shoveled rebound, you know what it's like, and they all have! You can appreciate their level of dedication in conducting research projects in this field using full-scale equipment. I am indebted to all of them and they have my gratitude.

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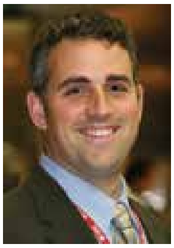

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