Material Velocity at the Nozzle

By Nicolas Ginouse and Dr. Marc Jolin

Since the early days of shotcrete, the reduction of rebound has been one of the major technical challenges of the industry due to its obvious impact on material and labor costs and, although less recognized, its detrimental effect on material properties. Although today, rebound mechanisms are still poorly understood from a physical and mathematical point of view, it has been shown that the impact velocity of particles plays an essential role on shotcrete rebound (Armelin et al. 1999). It is, therefore, essential to have a precise idea of the impact velocities generated by a given shotcreting configuration (for example, nozzle type, process, distance, and angle) in order to allow optimization of rebound. In practice, shotcrete material velocity is adjusted by changing the input airflow at the gunning machine in dry-mix shotcrete or at the nozzle in wet-mix shotcrete. These adjustments are currently based on the nozzleman and machine operator's experience.

This "Technical Tip" presents the experimental setup developed in the Shotcrete Laboratory at Laval University in Québec, Canada, to measure particle velocities at the nozzle outlet. Velocity values obtained for dry- and wet-mix shotcrete will also be discussed. In order to reproduce a realistic shotcrete spray, shotcreting equipment and mixtures common in the industry were used. An Aliva 246.5 with a 0.95 gal. (3.6 L) electric rotor and a 1.5 in. (37 mm) double-bubble nozzle (Fig. 1) were used for the dry-mix process. For the wet-mix shotcrete, an Allentown Powercreter 10 pump and a 2 in. (50 mm) hose with a short rubber "convergent" nozzle (Fig. 2) were used. In both cases, conventional dry and wet shotcrete mixtures supplied by King Packaged Materials were shot.

A pressure gauge and an electronic airflow meter were used to measure the input air pressure and the volume of airflow, respectively. The input air pressure was kept constant and equal to 100 psi (700 kPa) for all shotcreting tests. For the velocity measurements, a high-speed imaging system with a 1250 frames-per-second capacity was used to film the shotcrete spray. As illustrated in Fig. 3, this high-speed camera was placed perpendicular to the horizontal nozzle axis to visually capture the entire stream of particles. Note that for these measurements, the nozzle was kept motionless because the goal was to study the material as it exited the nozzle.

One of the most impressive portions of the setup was the software for the image analysis. The software tracked, frame by frame, the recorded particle's position as it exited the nozzle (refer to Fig. 4) to deduce nozzle velocity. A second analysis system included an in-house Matlab® program to correct optical errors induced by the camera lens and positioning.

The experimental measurements show that the particle velocities are not uniformly distributed around the (horizontal) spray axis. Indeed, in both configurations (dry and wet), the maximum

Fig. 1: Double-bubble dry-mix nozzle

Fig. 2: Rubber wet-mix nozzle (Bolduc 2009)

velocity is reached along the spray axis—that is, the centerline—and reduces gradually toward the edges of the spray. More precisely, centerline velocities obtained in dry- and wet-mix shotcrete are respectively about 1.75 and 1.32 times higher than the velocities measured at the spray edges. The maximum centerline velocity is about 78.3 mph (35 m/s) with the double-bubble nozzle (dry), decreasing gradually to 44.7 mph (20 m/s) at the spray edges. In the wet-mix case, velocity distribution is more uniform; the velocity difference is lower with a centerline velocity equal to 73.8 mph (33 m/s) and an edge velocity of 55.9 mph (25 m/s). The nozzle type and process can explain

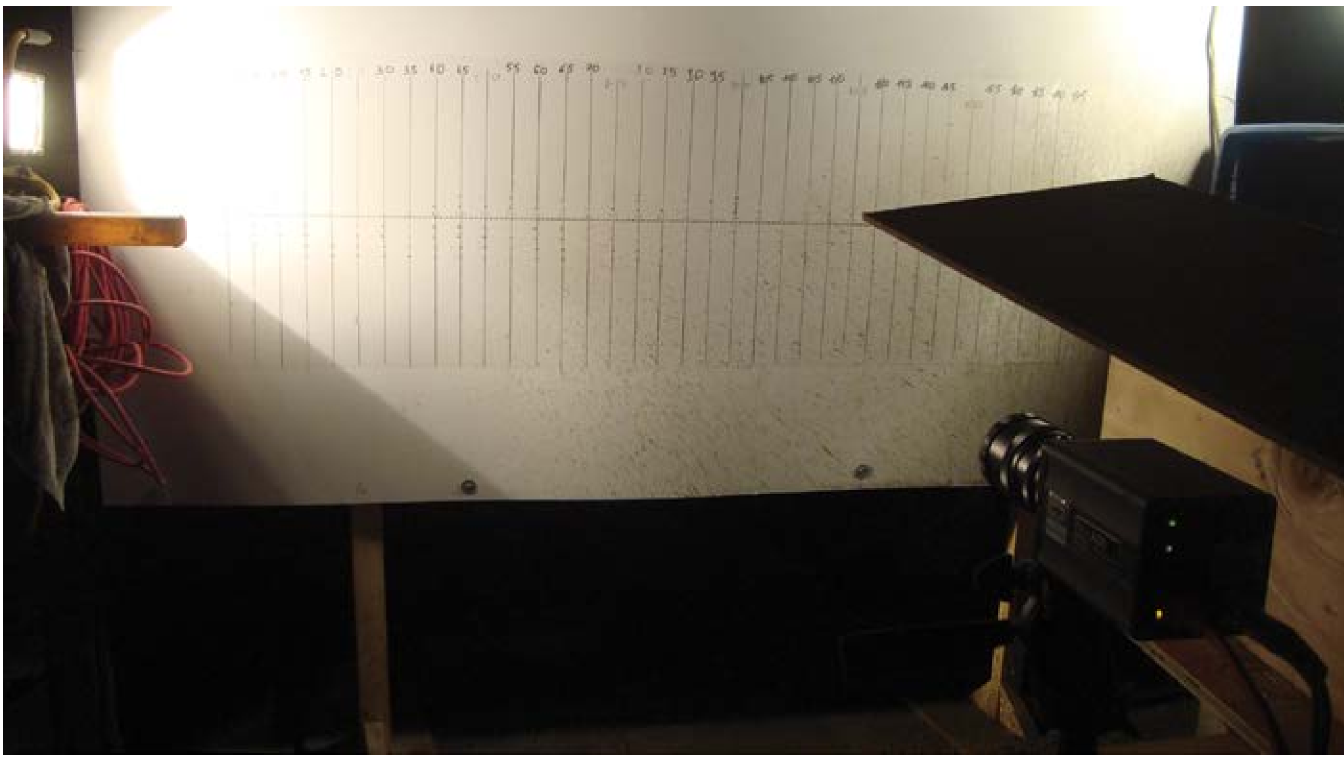

Fig. 3: High-speed camera ready to film a shotcrete spray

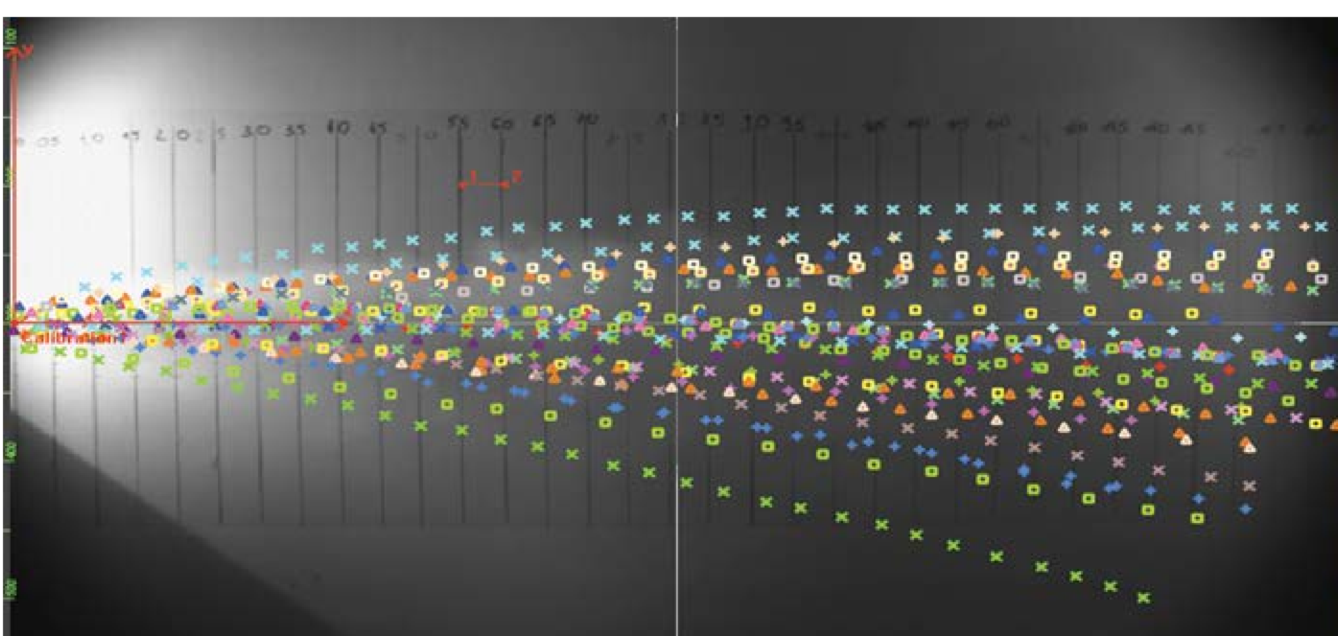

Fig. 4: Particle tracking performed using image analysis software (Jolin and Ginouse 2012)

this difference in velocity distribution. First, the double-bubble nozzle used in dry-mix shotcrete induces more turbulence, slowing down peripheral particles, compared with a "convergent" wet-mix nozzle where the air ring seems to produce the opposite effect. Second, the existence of a lubricating layer formed within the delivery hose during pumping can also facilitate peripheral particle acceleration by reducing friction with the internal nozzle walls (Kaplan et al. 2005). Indeed, according to yet-unpublished work conducted in Laval University's lab on wet-mix shotcrete, the periphery of the wet-mix spray contains more cement paste and fine aggregates compared to its core. Therefore, this lubricating layer appears to be conserved while passing through the nozzle, confirming its potential effect on peripheral particle acceleration.

The average velocities calculated from the centerline and edge velocities provide further information on the effect of equipment and process on outlet velocity. In both cases, average velocities are very similar (61.5 mph [27.5 m/s] for dry-mix and 64.9 mph [29 m/s] for wet-mix). In our experiments, we used the same input airflow of 200 ft^3/min (5.7 m^3/min) for both processes. Although it is commonly believed that wet-mix shotcrete requires less pneumatic energy to accelerate the particles than the dry-mix process, in which airflow is also used to convey dry material from the gunning machine to the nozzle, the same input airflow generated similar average velocities. To explain this somewhat unexpected similarity, we must also consider the amount of material (mass) that is accelerated or conveyed in each process. In fact, even if the dry-mix shotcrete configuration required more airflow to reach a given average outlet velocity, our wet-mix shotcrete case required acceleration of about three times more material (in term of mass). The output mass rate (pumping rate) was about 6.2 lb/s (2.8 kg/s) with the Powercreter 10 against 2.0 lb/s (0.9 kg/s) with the Aliva 246.5.

Based on the results presented, it is the nozzle type, the shotcrete process, and the output rate of material that will primarily affect the outlet velocity distribution. Moreover, in the wet-mix process, the lubricating layer induced by the pumping phase and the air ring positioning seem to provide favorable conditions to create a more uniform velocity distribution out of the nozzle. The next phase of this research will take advantage of the complete velocity profiles generated and concentrate on the material rebound phase of the application process. It is believed that, once equipped with experimentally validated velocity profiles, the description and optimization of rebound is just around the corner.

References

Armelin, H. S.; Banthia, N.; and Mindess, S., 1999, "Kinematics of Dry-Mix Shotcrete," *ACI Materials Journal*, V. 96, No. 3, May-June, pp. 283-290.

Bolduc, L.-S, 2009, "Étude des propriétés de transport du béton projeté," M.Sc. thesis, Université Laval, Québec City, QC, Canada.

Jolin, M., and Ginouse, N., 2012, "Recent Research in Wet-Mix Shotcrete at Laval University," *Proceeding of the 3rd Brazilian Congress on Tunnels and Underground Structures,* São Paulo, Brazil, Mar. 20-22. pp

Kaplan, D.; Larrard, F. D.; and Sedran, T., 2005, "Design of Concrete Pumping Circuit," *ACI Materials Journal*, V. 102, No. 2, Mar.-Apr., pp.110-117.

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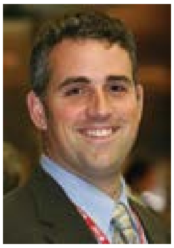

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