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Effect of equipment on spray velocity distribution in shotcrete applications

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HIGHLIGHTS

- The impact velocity fields produced by three shotcrete nozzles are investigated.
- A novel experimental approach using a high-speed imaging system is proposed.
- The effect of equipment on spray features is revealed using normalized parameters.
- The axial velocity profiles at the nozzle outlet follow a Gaussian-type function.
- A mathematical expression of the spray velocity fields investigated is provided.

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ABSTRACT

It is well known that the velocity of particles exiting the nozzle plays a central role on rebound and consolidation in the shotcrete placement process. With this in mind, the impact velocity distribution was investigated using a high-speed imaging system with a full-scale shotcrete spray generated using two dry-mix nozzles and one wet-mix nozzle. The incident velocity was found to be at its maximum in the central region around the spray axis and decrease toward the peripheral regions following a Gaussian-type function. Further analysis using normalized parameters shows that these velocity profiles, which were obtained experimentally, follow a similar function that can be used to compare the effect a given nozzle, or equipment, has on impact velocity distribution. In light of this work, innovative and unique characterization tools are proposed to further support equipment optimization and to improve the understanding of the overall shotcrete process, and especially rebound.

1. Introduction

Since the early days of the shotcrete process, the major goals of the industry have been to reduce rebound and improve the material placed. In addition to an obvious negative impact on cost-efficiency, it has been proven that the rebound of aggregates or fibers directly affects the properties of in-place material [1–4]. Even though mixture design adjustments can improve material placement and properties [5–11], there are still many unknowns related to the placement process, such as material velocity, impact, consolidation and rebound. Some studies dealing with rebound [3,6,12–14] have determined that material impact velocity plays a central role on the rebound phenomenon. Indeed the impact kinetic energy, which is function of the particle mass and the square of the impact velocity, is a first order parameter controlling the rebound of aggregates [3]. As a result, understanding the spraying phenomena directly controlling shotcrete kinematics (velocity), and therefore the impact conditions, is considered essential to further the understanding and improvement of the shotcrete process. Although a single particle shooting setup has been used to measure incident particle velocity [2,13,15,16], it reveals that a complete characterization of the material spray is necessary to understand and investigate the mechanisms that will enable further rebound reduction and, more generally, the effects equipment and mixture design have on the placement process.

In this context, this paper presents a complete characterization of the spray velocity field obtained for three different nozzles used in wet- and dry-mix shotcrete applications. The experimental data was collected using a high-speed camera and imaging system. New analytical tools involving normalized parameters are discussed, as

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they enable a unique comparison of velocity distributions generated by different equipment. In order to understand the role of each velocity component on the impact conditions, the entire axial and radial velocity fields are assessed and analyzed. For the three nozzles considered in this study, a complete description of their spray velocity fields is provided.

2. Kinematic parameters

The first step of kinematic characterization consists in defining a coordinate system that can be used to measure the location of particles and then calculate their velocities. In this case, particle coordinates are obtained from the Cartesian base system (x,y) described in Fig. 1, the origin of which is located at the center of the nozzle outlet section. In this study, the nozzle is oriented horizontally, and gravity acts on the inflight particles in a vertical downward direction.

The local particle velocity $\vec{U}(x,y)$ can be decomposed into a radial component $\vec{v}(x,y)$ and an axial component $\vec{U}(x,y)$. Physically, the radial velocity tends to disperse the particles away from the nozzle axis, while the axial velocity is oriented with the spraying direction.

3. Materials and methods

In order to produce a realistic shotcrete spray, conventional spraying equipment and mixtures commonly employed in the industry were used. The only departure from conventional shooting practice is that the nozzle was held motionless. Since the interest of this research lies in the *spray* of material, and not the *in-place* material, this stationary nozzle shooting is without consequence and even facilitates image capturing.

3.1. Sprayed material

Two pre-packaged concrete mixtures that are commonly employed in wet- and dry-mix shotcrete applications were used in this study. Both mixtures contain fine and coarse aggregates that follow ACI Gradation No. 2 [17], ordinary Portland cement and silica fume. Mix designs are detailed in Table 1.

The dry pre-bagged mixtures were produced as two large single batches in a packaging plant. All aggregates were oven dried before packaging to avoid cement hydration.

3.2. Shotcrete equipment

Conventional dry- and wet-mix shotcrete equipment was used to spray the material. In all cases, the airflow was measured and adjusted using an electronic airflow meter, while the air pressure was monitored by a pressure gauge (Fig. 2a). In this study, the airflow volume was kept constant at 5.7 m^3/min (200 CFM), and the monitored air pressure was equal to 6.9 bars (100 PSI).

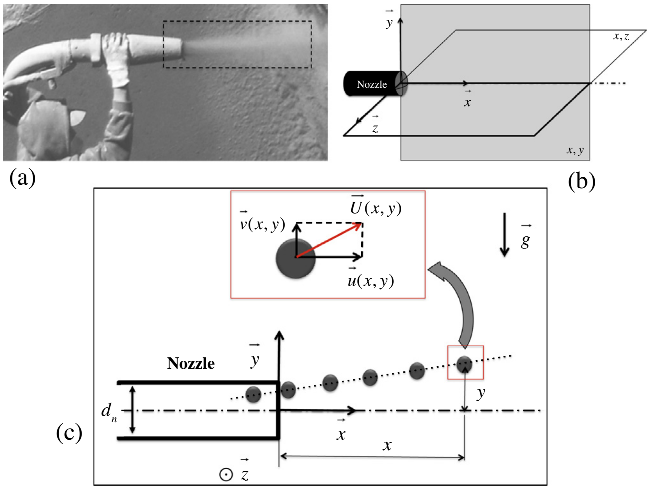

Fig. 1. (a) Example of typical shotcrete spray with the region of interest in the dotted rectangle, (b) spatial coordinate system and (c) coordinate system and velocity nomenclature.

Table 1
Mix design of the pre-packaged mixtures used in dry and wet-mix shotcrete.

Ingredients	Dry-mix	Wet-mix
Ordinary Portland Cement (kg/m^3)	396	373
Silica fume (kg/m^3)	35	33
Gravel – 2.5–10 mm (kg/m^3)	600	564
Sand – 0.08–5 mm (kg/m^3)	1134	1068
W/B	0.40[a]	0.50
Air (vol.%)	4%[a]	5.5%[b]

[a] Estimated value.
[b] Measured following ASTM C143.

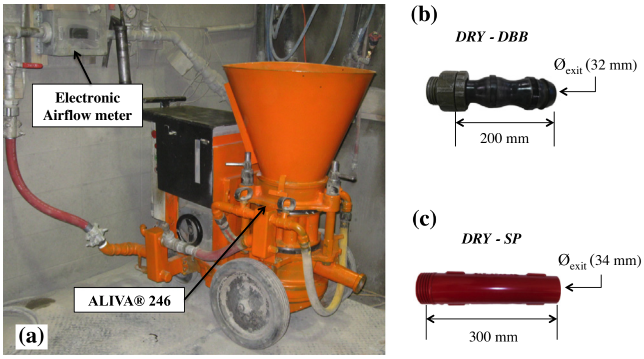

Fig. 2. (a) Dry-mix shotcrete gun and (b and c) dry-mix shotcrete nozzles used in this study.

3.2.1. Dry-mix process

An ALIVA® 246 rotating barrel machine connected to a 15 m long hose with an inside diameter of 38 mm was used for the dry-mix process (Fig. 2a). In order to evaluate the effect of the equipment on the spray characteristics, two types of nozzle (Fig. 2b and c) were used. Both nozzles have a specific inside shape that produces turbulence to enhance mixing of the material before spraying. The first nozzle, the self-described double-bubble nozzle (*DRY-DBB*), has two restriction and widening portions, purposefully maximizing turbulence and thus improving mixing of the water just introduced through the water ring and the conveyed dry material. The second dry-mix nozzle, *DRY-SP*, has a slightly tapered shape with molded helical grooves on the inside wall for improved mixing action.

Once the dry mixture was inserted into the dry-mix gun hopper (Fig. 2a), the airflow was adjusted. Spraying started once the electric rotor was turned on, allowing the dry material to flow through the rotating barrels and be introduced into the delivery hose. In order to properly wet the dry mixture, the mixing water was introduced via a water ring placed 3 m upstream of the nozzle outlet. An electronic water flow meter and a needle valve were used to measure and manually adjust the amount of water added to the conveyed mixture. The mixture was adjusted for proper consistency [18] prior to image capture.

3.2.2. Wet-mix process

Conventional wet-mix shotcrete equipment was used to spray the material (Fig. 3). The shotcrete piston pump (Fig. 3a) used to deliver the fresh mixture to the nozzle was connected to a 20 m long hose having a 50 mm inside diameter. A short rubber nozzle (Fig. 3b) commonly employed in hand-held wet-mix applications was used to spray the pumped material. Note that in this case, the nozzle had an air ring to expel the pumped concrete and accelerate it toward the receiving surface.

Before pumping the pre-packaged mixture, a Portland cement grout with the same water-to-binder ratio as the sprayed mixture (0.50) was pumped through in order to lubricate the delivery hose. Then the dry mixture was mixed with the water for 2 min and fed directly into the pump. The airflow was adjusted to 5.7 m^3/min (200 CFM) before spraying began.

3.3. High-speed imaging system

In order to measure the x–y velocity field, the spray of particles exiting the nozzle was filmed using a high-speed camera placed perpendicular to the nozzle axis. Once spraying started, the high-speed camera (with a 1250 frames-per-second capacity) recorded particle positions, as shown in Fig. 4. A camera calibration procedure developed in [19–21] that uses a Matlab® program was applied to each image in order to remove optical errors induced by the camera lens and positioning. A similar system was also satisfactorily used in [2,15]. The velocity values were