A Study on Low-Velocity Sprayed Mortars

By Christine Poulin and Marc Jolin

INTRODUCTION

One of the most significant challenges in civil engineering is the rehabilitation and repair of deteriorated reinforced concrete infrastructure. Many techniques exist to ensure reliable and safe structural repairs, and one of them, known for its unique high-velocity pneumatic placement process, is shotcrete. Thanks to this high-velocity process, shotcrete generates substantial material consolidation to ensure proper reinforcement encapsulation and excellent adhesion to the repaired surface. It commonly removes the need for complex formwork while allowing for rapid execution of work, resulting in significant economic advantages. Shotcrete is the key to many complex construction scenarios, such as curved and irregular architectural shapes, repairs with little or no downtime, infrastructure with narrow and difficult access, and it even works in remote areas.

A different pneumatic placement technique that seems to have grown in popularity in recent years for structural repairs is low-velocity sprayed mortar (LVSM). This process, initially used in the construction and renovation fields to replace hand-applied mortar with a trowel, differs from shotcrete by the very low velocity of its particles during spraying. The system uses a small pump that pushes the fully mixed material at the nozzle, spraying it at low velocity onto a receiving surface. This technique is used for several types of application, such as surface covering, aesthetic renovations, coating for fire protection, sandwich panels, and more recently, concrete repairs. However, LVSM applicability to structural repairs remains to be demonstrated due to the lack of technical information in the industry. The presence of reinforcing bars and the relatively thicker applications in most structural repairs may present serious challenges for the quality of LVSM placement.

While shotcrete relies on high-particle velocity to provide in-place material consolidation to meet structural repair requirements, LVSM relies instead on a slightly adapted material rheology to allow consolidation with minimal energy. Although the LVSM process represents a spray-on approach to placing thin layers of repair material, its ability to generate adequate structural repair must be investigated, particularly from the standpoint of reinforcement encapsulation and substrate adhesion.

Based on an extensive research and development project conducted in the Shotcrete Laboratory at Université Laval entitled “Low-Velocity Sprayed Mortar and Shotcrete: what are the differences?,” this article’s purpose is to present interesting data about LVSM, including material properties and durability, substrate adhesion, placement technique, rebound, reinforcement encapsulation, and material velocity. (Poulin, 2019).

EQUIPMENT

The International Concrete Repair Institute (ICRI) defines LVSM as “the placement of a repair material by spraying using a low-velocity pump with air added at the nozzle” (ICRI, 2023). Indeed, to achieve low-velocity spraying, the equipment required is essentially a rotor-stator pump with nozzle and hose, a small air compressor, and a mortar mixer, as shown at Fig. 1.

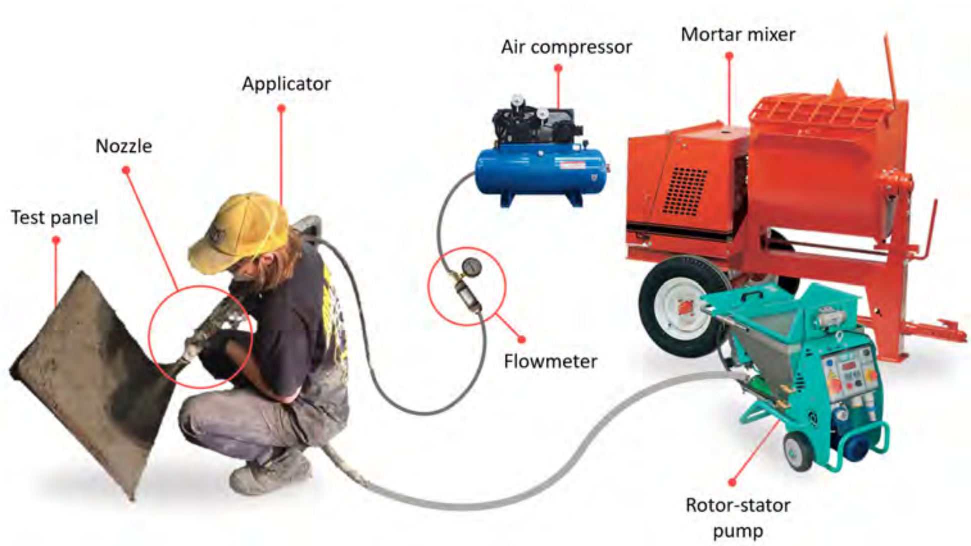

Fig. 1: LVSM system built in the Shotcrete Laboratory.

There is quite a variety of equipment available in the industry for LVSM systems. IMER's Mighty Small 50 pump was chosen for the experiment with a recommended 18 CFM air compressor. A flowmeter system was also included in the compressed air supply line to monitor the airflow during placement.

The selection of an appropriate nozzle along with adequate airflow was found to be the most important set of parameters influencing the overall quality of LVSM placement and the properties of the material in-place. There are different types of nozzles for distinct jobs with the low-velocity process, as shown in Fig. 2a and 2b.

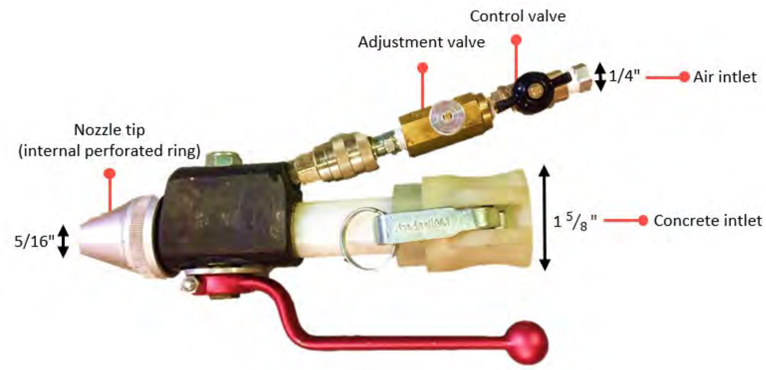

Fig. 2a: LVSM nozzle no. 1 used in the research project.

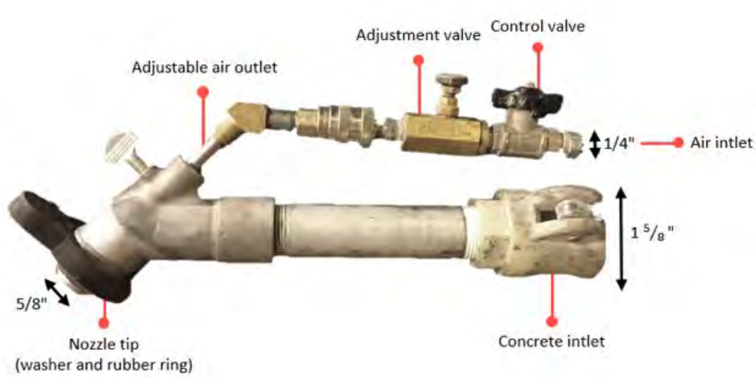

Fig. 2b: LVSM nozzle no. 2 used in the research project.

Both nozzles used for LVSM had different configurations that significantly influenced the sprayed mortar stream. As detailed in Fig. 2a, the tip of nozzle no. 1 includes a perforated ring for air supply, while Figure 2b shows nozzle no. 2, which is frequently used for stucco finishing work, uses only one direct air outlet. These nozzles were modified with an appropriate system of adjustment and control valves for better accuracy when adjusting airflow during the experiment.

The LVSM system selected for this experiment was tested with three repair products specifically designed to be applied by low velocity. The mortar mixes selected were the Planitop 12 SR from MAPEI, the MasterEmaco S 488CI from BASF, and the Tamms Structural Mortar from Euclid Chemical. These pre-packaged mixes were tested by spraying in the laboratory without knowledge of their composition and mixture design. The amounts of water added to the mixes were determined by testing the different dosages recommended by the manufacturers. The water content chosen for each mix was selected for its best response in the pump, going through the nozzle, and during placement of the material.

MATERIAL PROPERTIES AND CHARACTERISTICS

At the Shotcrete Laboratory in *Université Laval*, the results were obtained with samples of sprayed mortars at low velocity. The properties and characteristics for Planitop 12 SR, MasterEmaco S 488CI, and Tamms Structural Mortar were all comparable with both nozzles. Therefore, only the results obtained with Planitop 12 SR are presented in Table 1. For the results on wet-mix shotcrete, the properties and characteristics are based on previous studies conducted on shotcrete and the ACI guide (ACI PRC 506-22, 2022). It should be noted that the properties and characteristics presented for wet-mix shotcrete show what is generally obtained with this process. The results found in the literature for shotcrete are variable and depend considerably on the composition of the concrete mixtures and their consistency.

According to the results presented in Table 1, both shotcrete and LVSM produce very high-quality materials based on the mechanical properties and material durability. Compressive strength, resistance to chloride ion penetration, and resistance to freeze-thaw cycles are excellent with both high and low velocity. Shotcrete does not seem to resist as effectively to the aggressive conditions simulated in the laboratory for the de-icing salt scaling tests, while LVSM shows slightly higher porosity and absorption. Despite these comparisons, the results presented remain excellent for both processes.

Just like for shotcrete, the bond strength tested provides excellent results with LVSM on a concrete substrate with a compressive strength of 32 MPa (4700 psi). For each test performed, the failure patterns of the specimens were found at the substrate. For surface preparation, the concrete substrate was brought to an ICRI CPS-5 and saturated surface dry (SSD) condition prior to spraying the material. Despite limited consolidation velocity, LVSM provides adequate adhesion to the substrate. The composition of the mortar mixes is a definite cause of the excellent ability of the repair material to bond to another substrate. The results shown demonstrate that the LVSM mixture design is of very high-quality and requires very little consolidation energy. However, it must be said a pre-packaged LVSM bag costs about three to four times that of a pre-packaged bag of wet-mix shotcrete.

Besides the excellent mechanical and durability properties, several elements between wet-mix shotcrete and LVSM

Table 1: Comparison between shotcrete and LVSM

Properties and characteristics	Wet-mix shotcrete	LVSM	
		Nozzle no. 1	Nozzle no. 2
Compressive strength at 28 days ASTM C1604 – Shotcrete ASTM C109 – LVSM	28 to 41 MPa and even > 83 MPa (4,000 to 6,000 psi and even > 12,000 psi) (ACI506-22, 2022)	63 MPa* (9,140 PSI) *mortar cubes	61 MPa* (8,850 PSI) *mortar cubes
Resistance to chloride ion penetration – RCPT ASTM C1202	689 to 862 C (using silica fume) (Bolduc, 2009)	735 C	868 C
Freeze and thaw – durability factor ASTM C666-A	97 to 102% (D. R. Morgan et al., 1988)	96%	94%
De-icing salt scaling ASTM C672	0.02 to 3.46 kg/m^2 (Beaupré, 1994)	0.32 kg/m^2	0.27 kg/m^2
Porosity ASTM C642	14 to 17% (ACI506-22, 2022)	18%	22%
Absorption ASTM C642	6 to 8% (ACI506-22, 2022)	9%	11%
Bond strength ASTM C1583	> 1 MPa (145 psi) (ACI506-22, 2022)	> 2.0 MPa (290 psi)	> 2.4 MPa (350 psi)
Spraying technique	Direct the nozzle perpendicular to the surface while rotating the nozzle in a series of small oval or circular patterns. (ACI506-22, 2022)		
Technique for encapsulating reinforcement	Perpendicular to the reinforcing bars at sufficient velocity	Start with nozzle tip pointing behind reinforcing bar and build out to desired thickness*	Impossible
Material thickness – vertical	Up to 200 mm (8 in.) without accelerator	< 50 mm (2 in.)	
Distance of spraying	0.6 to 1.8 m (2 to 6 ft) (ACI506-22, 2022)	0.3 m (1 ft)	
Rebound	10 to 15% (ACI506-22, 2022)	Negligible	
Reinforcement encapsulation**	Feasible: the maximum bar size and steel congestion will be function of mix design, equipment and shotcreter's experience	Very difficult, requires specific procedure. Practically impossible if many or large diameter bars.	Impossible
Spraying velocity – maximum	33 m/s (73.8 mph) (Ginouse & Jolin, 2013)	4.5 m/s (10 mph)	2.6 m/s (5.8 mph)
Air flow rate	200 CFM (Ginouse & Jolin, 2013)	5 CFM	11 CFM

* Material does not flow naturally around the bar; the applicator must adapt the placement pattern accordingly.
** According to an ACI-C660 certified examiner.

are very distinctive. The following sections will focus on the findings with LVSM in terms of placement technique, rebound, reinforcement encapsulation, and velocity.

PLACEMENT TECHNIQUE

LVSM placement technique differs mainly because of the particle velocity sprayed through the nozzle. Despite the attempts in the laboratory, the traditional shotcrete placement techniques could not be imitated by the LVSM. Based on the experiment, when spraying perpendicular to a receiving surface, the distance from the nozzle must be reduced to 0.3 m (1 ft) with a small circular motion. Depending on the mortar mixes, the maximum material thickness in one layer would be less than 50 mm (2 in.) vertically. Otherwise, the fresh material in place has no hold and runs off the surface by gravity.

When encapsulating reinforcing bar, the most effective placement technique identified, especially with nozzle no. 1 (Fig. 2a), is to start with nozzle pointing directly behind the reinforcing bar and build out to desired thickness by spraying the material in successive layers. Due to the low velocity, the material does not flow from the front to the rear of the reinforcing bar, which will leave voids. The efforts needed for full encapsulation of the reinforcing bars with LVSM required a significant amount of time and attention, even under controlled and optimal laboratory conditions.

A certification offered by ACI for shotcreters (formerly called shotcrete nozzleman) ensures a minimum level of workmanship, whereas no certification appears to be available or required for the low velocity mortar spraying process. The results demonstrated that the applicator must adapt to new conditions with LVSM to ensure a good quality of material in-place and limit operating problems during spraying. However, the absence of regulatory documentation surrounding LVSM leaves room for any applicator with or without experience to use LVSM at their convenience without the appropriate knowledge, which can lead to poor quality work.

REBOUND

Unlike shotcrete, which generates significant rebound, it was observed during the experiment that practically no rebound was generated with LVSM. In fact, most of the material adhered to the receiving surface. Following the model developed by Armelin & Banthia (1998), it appears the properties of the freshly applied substrate created by the LVSM and the low kinetic energy of the particles (associated to the low velocities) combine to produce very favorable conditions to drastically reducing rebound. This is an advantage for LVSM. However, even if there is no rebound production, the price of the LVSM material is still much higher than the price of wet-mix shotcrete including rebound, and thus does not provide an economic benefit.

REINFORCEMENT ENCAPSULATION

Inspired by the ACI shotcreter certification (ACI, 2015), reinforcing bar encapsulation tests with LVSM were performed with the placement technique developed in the research laboratory. The conventional certification panel was reduced by half for LVSM testing, and the evaluation of the reinforcing bar encapsulation was performed by an ACI-approved examiner. The results obtained with both LVSM nozzles are shown in Table 2.

Under controlled and optimal laboratory conditions, it was possible with great effort and care to achieve successful reinforcing bar encapsulation at 5 CFM of airflow with the use of nozzle no. 1 (Fig. 2a). However, the results obtained with nozzle no. 2 (Fig. 2b) were poorer and inadmissible in accordance with the regulations of the ACI shotcreter certification program (ACI, 2015).

This demonstration shows that specific conditions must be followed to perform small structural repair with LVSM, such as the use of nozzle no. 1 (Fig. 2a) with a single row of reinforcing bars with full access to the rear. However, under typical field conditions, LVSM might not be suitable as a replacement for shotcrete due to the location and number of reinforcing bars, and the thickness of the repair. Shotcrete

Table 2: LVSM reinforcement encapsulation

Core #	1	2	3	4	5
Nozzle no. 1					
Ranking	**1**	**1**	**1**	**1**	**1**
Nozzle no. 2					
Ranking	**5**	**5**	**5**	**4**	**4**

remains the only pneumatic placement technique to achieve adequate structural repair of all kinds, which has been ensured by standards, technical guides, and certification programs.

VELOCITY

By using a similar procedure as used before for shotcrete research, the velocity profiles were calculated for the LVSM with nozzle no. 1 and nozzle no. 2. Based on the shape of the spray pattern, the velocities of particles, and the quality of the material being placed, the most efficient results and preferred combination were at 5 CFM with the nozzle no. 1 and at 11 CFM with the nozzle no. 2.

The velocity profile with nozzle no. 1 at 5 CFM was distributed over a vertical distance of approximately 130 mm (5 in.) as presented in Fig. 3a and 3b. At 300 mm (12 in.) from the origin, the maximum particles velocities concentrated in the center of the distribution were reaching 4.5 m/s (15 ft/s), while those present at the periphery of the spray were slower by about 1 m/s (3.3 ft/s) from the center.

Regarding nozzle no. 2: the velocity profile selected at 11 CFM was distributed over a vertical distance of approximately 140 mm (5.5 in.) as presented in Fig. 4a and 4b. With the same distance from the origin, the maximum particles velocities were reaching 2.6 m/s (8.5 ft/s). There was no concentration of maximum speeds at the center of the distribution.

The decrease in velocities generated by the LVSM is very significant compared to the 33 m/s (110 ft/s) at 200 CFM by wet-mix shotcrete presented in the work of Ginouse and Jolin (2013). The velocity reductions created by using LVSM are 86% with nozzle no. 1, and 92% with nozzle no. 2.

Regardless of the level of velocity, the material properties tested during the LVSM experiment always met manufacturer specifications in terms of strength and durability. Consequently, the only criterion for any type of pneumatic process would be the use of sufficient consolidation energy to obtain quality material in-place, whether at high or low velocity. In fact, the energy required to consolidate the material would depend on the velocity threshold dictated by the pneumatic process, the equipment used, the rheology, and the composition of the mixture.

CONCLUSION

The present experiment conducted in *Université Laval* addresses some misconceptions about the uses of LVSM.

Fig. 3a: LVSM particles spray at 5 CFM with nozzle no. 1—recorded image for speed calculation.

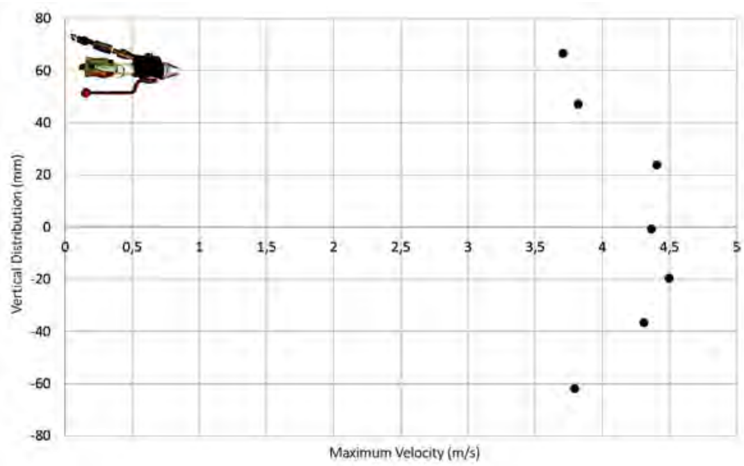

Fig. 3b: LVSM particles spray at 5 CFM with nozzle no. 1—velocity profile.

Fig. 4a: LVSM particles spray at 11 CFM with nozzle no. 2—recorded image for speed calculation.

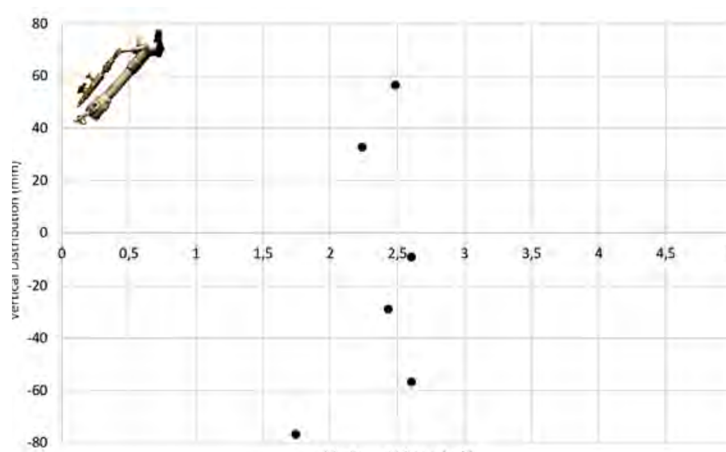

Fig. 4b: LVSM particles spray at 11 CFM with nozzle no. 2—velocity profile.

Indeed, the results shown that LVSM can produce durable works, as is the case with shotcrete. Whether at high or low velocities, sufficient consolidation energy is the key to achieving proper work and obtaining high-quality material. However, where reinforcing bars (or other obstacles) are to be encapsulated under typical field conditions, LVSM is not suitable due to its specific application conditions and poor results obtained during the present experiments. Consequently, shotcrete remains the only pneumatic placement process that can perform adequate structural repairs of all kinds, ensured by standards, technical guides, and certification programs.

Although LVSM should not be used for small structural repair, the advantages from LVSM can be promising for non-structural concrete repair applications, i.e. without reinforcing bar. However, technical support, such as a credible guide and specifications, must be created in the industry to ensure the in-place quality of work. Today LVSM is used by both experienced or inexperienced applicators, which can lead to potential poor-quality repairs.

Finally, LVSM shows that a slightly adapted rheology allows consolidation of the material with minimum energy. Therefore, would it be possible to find a middle ground between the energy required to consolidate material and an optimized rheology to produce shotcrete with low rebound production? The high energy required to consolidate shotcrete is physically demanding and leads to difficult working conditions, especially with the production of rebound. If a right balance between energy and rheology could be found, would shotcrete be more appreciated by all industry players and valued as sustainable for new generations? Research should focus on this aspect and see how to evolve shotcrete for a promising future.

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