

Pneumatically Applied Concrete: A Confusion of Terminology

By Charles Hanskat

In recent years, we've heard and seen the term "pneumatically applied concrete" (PAC) used in many discussions and specifications. The term seems straightforward, as it simply describes the act of placing concrete (or mortar) by flow of air through a nozzle. However, we are now seeing specifiers and owners specifying PAC, and apparently not fully understanding the variety of pneumatically placed methods in modern concrete construction and repair.

Evolution of Terminology

According to ACI 506R-16, "Guide to Shotcrete," the term "pneumatically applied mortar or concrete" (PAM or PAC) evolved as a rather generic term early in the 1900s after the proprietary term "gunite" was first established for what we now refer to as the dry-mix shotcrete process. In the 1930s, the American Railway Engineering Association (now known as AREMA) created the term "shotcrete" to replace the proprietary term "gunite" in railroad concrete works. In 1951, the American Concrete Institute (ACI) adopted the AREMA term "shotcrete" because use of tradenames in technical documents was frowned upon. As the wet-mix process developed soon

thereafter, it too adopted the term "shotcrete." "Sprayed concrete" is often used in lieu of the term "shotcrete" in other countries around the world.

As concrete repair materials became more specialized than the original sand and cement mortars, a new process, "low-pressure spraying," was introduced as a method of application to replace hand troweling of spalls. Concrete spall repair sections that the method were designed for were thinner and generally didn't require a high production rate of material placement. Although these spalled sections could certainly be shotcreted, the low-pressure sprayers required less equipment investment, less nozzleman expertise, and due to lower pressure, could be used in tighter spaces with less rebound. However, successful application with low-pressure spraying generally required proprietary, prepackaged cementitious products.

Shotcrete

As we look at the variety of application methods that may be considered PAC, let's first



Fig. 1: Dry-mix gun in early 1900s



Fig. 2: Graco low-pressure mortar sprayer

look at shotcrete. ACI CT-16 Concrete Terminology defines shotcrete as “concrete placed by a high-velocity pneumatic projection from a nozzle.” This terminology comes from ACI Committee 506, whose membership includes contractors, engineers, suppliers, and educators intimately involved in the shotcrete business. The key in this definition is high velocity. A study at Laval University by Ginouse and Jolin (*Shotcrete* magazine, Fall 2013) studied particle speeds in both dry- and wet-mix and found average particle speeds in the dry-mix material stream ranging from 45 mph (20 m/s) at the edge to 78 mph (35 m/s) in the centerline. Wet-mix showed a velocity ranging from 56 mph (25 m/s) at the edge to 74 mph (33 m/s) in the centerline.

Why do we need high velocity? Shotcrete placement depends on impact force to compact the concrete, allow the material to flow around obstructions such as reinforcing bars, and minimize voids within the concrete section. Imagine the force of your car driving 60 mph (97 km/h) down the highway, and then impacting an immovable concrete object. There is a massive transfer of energy from the car (and in our case the concrete material) flying through the air, and then suddenly stopping upon impact. One of the prime aspects of proper shotcrete placement is shooting perpendicular to the substrate. This is important because then we’re recreating a head-on collision and imparting the maximum energy to consolidation, compaction, and densification of the material in place.

Another aspect of high-velocity shotcrete is high abrasion, and correspondingly excellent bond to existing concrete or previously shotcreted layers. In effect, we are abrasively blasting the substrate, immediately before exposing it to the fresh paste of the cement-rich shotcrete mixture. The impact also drives the fresh paste into the substrate, creating excellent bond of shotcrete when using proper materials, equipment (air compressor size appropriate for the delivery hose and nozzle), and nozzleman placement techniques. Also, using high velocity helps to force fresh material around the back of reinforcement to be embedded in the concrete section.

High velocity can be achieved by using proper air volume. Dry-mix requires more air flow because the full transport of the materials through the delivery hose is accomplished by the air flow. In wet-mix, material delivery is by mechanically pumping through the delivery hose, and air is added to accelerate the concrete mixture only at the nozzle. ACI 506R states that wet-mix shotcrete requires 200 to 400 ft³/min (5.7 to 11.3 m³/min) air volume at 100 psi (7 bar) and dry-mix 350 to 1000 ft³/min at 100 psi (10 to 28 m³/min at 7 bar).

When compared to other methods, such as low-pressure sprayed mortar, shotcrete has the



Fig. 3: Modern dry-mix shotcreting



Fig. 4: Wet-mix shotcreting of structural wall

potential for much higher volume and productivity. Wet-mix can use plant-batched concrete delivered in large ready mix trucks with many cubic yards (cubic meters) in every truck, batched with a concrete batching truck or site-mixed with pre-bagged mixtures in large “super sacks” or smaller individual bags. Dry-mix can similarly be batched with a concrete batching truck or site-mixed with pre-bagged mixtures in large “super sacks” or smaller individual bags.

Shotcrete has some of the most sophisticated concrete mixtures used in the concrete construction market. We shoot overhead and vertical areas, thin or thick, fast set or normal set, and straight or curved sections, delivered from tens of feet to thousands of feet from the supply location. This allows shotcrete to be used in a wide

variety of applications, including underground, foundation walls, ground support, repair or repurposing, domes, cylindrical tanks, pools, and skate parks. Shotcrete is likely one of the biggest users of silica fume and fibers. We also regularly use hydration control, shrinkage-reducing admixtures, and accelerating admixtures. We're even moving into the use of nanoparticle technology to enhance the application and performance of our shotcreted projects.

Shotcrete has many ACI consensus documents directly addressing both dry-mix and wet-mix processes, including ACI 506.2-13, "Specification for Shotcrete," and ACI 506R-16, "Guide for Shotcrete." There is also a comprehensive set of ASTM Standards (C1140, C1385, C1480, and C1604) clearly delineating testing requirements. Additionally, ACI has a well-defined and comprehensive certification for shotcrete nozzlemen in both wet and dry processes and in both vertical and overhead orientations.

Low-Pressure Mortar Spraying

According to ACI Repair Application Procedures, "Spall Repair by Low-Pressure Spraying" (RAP-3), "Similar to wet-mix shotcrete but sprayed at a much lower velocity, low-pressure spall repair spray comes in the form of prepackaged mortar. The spray is applied using small concrete pumps or heavy-duty grout pumps to force the low-slump mortar through a hose. Air is added at the nozzle to impel the mortar. Bond with the prepared substrate is achieved through a combination of proper surface preparation, low-velocity impact, and the material properties of the prepackaged mortar."

The pumped mortar is at a lower pressure than wet-mix shotcrete (200 to 500 lb/in.² [13.7 to 34.5 bar]), and uses very low air flow as compared to either wet-mix or dry-mix shotcrete (10 to 15% of the flow rate). As evidenced by the title of the RAP-3 document, the application method was primarily developed to replace hand troweling of repair material in areas of spalled concrete.

So how does this method compare to shotcrete? There is much less compaction force and surface abrasion of the substrate. Bond depends on the quality of the prepared substrate and mostly on the adhesive properties of the repair mortar. ACI RAP-3 indicates that all low-pressure, spray-applied repair materials are proprietary, prepackaged cementitious products. Finally, with such low pressure and velocity, it is difficult to produce the differential pressure between the air flow and the space behind reinforcement to produce an active flow of material around larger reinforcement. Thus, much of the low-pressure sprayed work is very lightly reinforced with wire mesh or very-small-diameter bars.

It should also be noted there are no clearly established technical standards for materials, equipment, and placement of low-pressure sprayed mortar. ACI RAP-3 appears to be the only document addressing low-pressure spraying but has minimal technical provisions in its less-than-four-page, non-mandatory language overview of low-pressure spraying. A future revision of International Concrete Repair Institute (ICRI) Technical Guideline No. 320.1R, "Guide for Selecting Application Methods for the Repair of Concrete Surfaces," will include more information, but the document is still under development. There is no equivalent to the ACI Shotcrete Nozzleman Certification, and there doesn't appear to be any directly applicable ASTM testing standards.

A "Hybrid" Placement Process

As shotcrete placement was evaluated for thicker, structural sections with dense reinforcement, a hybrid placement process has evolved. Sections with two or three layers of reinforcement, several feet thick, and with reinforcing bars up to No. 11 (No. 36M) have been successfully shotcreted by experienced shotcrete contractors. With dense reinforcement placed in multiple layers, the velocity of the shotcrete (once it reaches the back of the shotcreted section) may be significantly reduced due to impact with the reinforcing bars in the outer layer(s). With the reduced impact force from lowered velocity, the concrete may not be completely consolidated and supplemental consolidation must be supplied. This is usually achieved with a small pencil vibrator to keep the very low-slump concrete from shifting to the front of the section. In these thick sections, the outer layer of reinforcement may very well be properly encased by normal shotcrete techniques.

The shooting of these types of sections has been very successful, and due to the benefits of shotcrete placement including reduced formwork, efficient scheduling, flexibility in placement of the delivery hose, and overall improved sustainability. Being a hybrid process, some have used the term PAC to denote this type of work because the concrete is being placed pneumatically. As this is a developing placement technique, there are no clearly established standards for the hybrid application of shotcrete combining traditional shotcrete application with placing/vibrating. In the future, perhaps ACI 506 will address this hybrid system.

Sorting Out the Confusion of Terms

As you can see, "PAC" is a term applied (for right or wrong) to a variety of processes. PAC in the early 1900s was guniting, where there were no other possibilities. Today's PAC includes a much

more diverse set of processes. Wet-mix was added in the second half of the century and we now have low-pressure sprayed mortar and the hybrid shotcrete/place and vibrate processes. ICRI Technical Guideline 320.1R-92(96) very briefly covers wet-mix and dry-mix shotcrete. A future revision of the document is slated to include low-pressure sprayed mortar. All three will be included in “pneumatically applied methods.”

So at this time, a specifier or owner simply requiring “pneumatically applied concrete” doesn’t necessarily get you high-velocity, high-impact-force shotcrete. It may allow the low-pressure mortar spraying or a hybrid placement process. Low-pressure spraying by its inherent nature cannot provide high velocity, and thus has reduced ability to compact by impact and abrade the substrate to produce enhanced bond. Further, low velocity may well impair the ability of the mortar to flow around larger reinforcing bars and embeds.

ACI CT-16 doesn’t define PAC. However, it does define “pneumatically applied mortar — see shotcrete.” This would seem to exclude low-pressure sprayed mortar because it is pneumatically applied but certainly not at the high velocity required of shotcrete. We will work with ACI to get their terminology aligned with the industry.

So, in summary, what should we learn from this mix of terminology?

- Specifiers and owners need to be aware that PAC is NOT always shotcrete.
- Shotcrete requires high velocity for creating good bond, full compaction, complete encasement of reinforcing bars, and eliminating voids.
- If high-velocity placement cannot be maintained in the structural section due to obstructions (heavy reinforcement or embeds), alternative methods for compaction must be available to densify the concrete mixture in-place.
- Shotcrete has many ACI consensus documents directly addressing both dry-mix and wet-mix processes, including ACI 506.2-13 (Specification) and ACI 506R-16 (Guide), as well as a comprehensive set of ASTM standards for testing requirements.
- There are no clearly established standards for low-pressure sprayed mortar or the hybrid application of shotcrete combining traditional shotcrete application with placing and vibrating.
- Specifiers and owners should always specifically call out shotcrete when they desire placement at high velocity, high abrasion, compaction, and complete encasement of embedded reinforcement.
- When specifiers or owners require shotcrete, they should verify the shotcrete contractor is using equipment (air compressors/delivery

hose/nozzles) that produces enough air flow volume to propel the material at high speed.

In closing, over the last hundred years, we’ve seen shotcrete dramatically improve in the variety of uses, equipment, and quality. As shotcrete has evolved, so has the term “pneumatically applied concrete,” as it now covers a wider variety of concrete placement technologies. Those of us in the industry simply need to be aware of this evolution, and when specifying application methods, be specific about the particular type of application we need for our project.



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