Can Supplemental Consolidation Extend the Limits of Shotcrete Placement?

By Oscar Duckworth

In many major metropolitan regions of the United States, shotcrete methods are being used daily to place concrete within elements incorporating large, highly congested reinforcement layouts. In the past, many thought that only form-and-pour methods could be used for these dense layouts. The increased use of shotcrete for these applications is primarily driven by the cost and labor savings that inherently result from shotcrete's efficiencies. Because shotcrete's compaction and consolidation qualities are directly attributed to high velocity, lower velocity that can occur in tightly congested reinforcement configurations being shot today can prove insufficient to provide adequate compaction.

For years, experienced shotcrete crews have used a hybrid of high-velocity placement with supplemental consolidation methods. The supplemental mechanical vibration techniques help consolidate the concrete and allow full encasement of congested reinforcement elements. Success with the hybrid placement requires careful attention to detail and experience by the shotcrete crews.

Current shotcrete technical documents, ACI 506.2-13, "Specification for Shotcrete;" ACI 506R-16, "Guide to Shotcrete;" and ACI CP-60, "Craftsman Workbook for ACI Certification of Shotcrete Nozzleman," do not recognize the use of mechanical vibration during shotcrete placement. Lack of published guidance can lead to confusion for engineers, specifiers, and on-site inspectors if a vibrator is operated in conjunction with shotcrete placement.

Fig. 1: Mockup panels with congested reinforcement patterns may require alternative methods to attain adequate consolidation

Is the shotcrete industry comfortable with this hybrid placement process? Can the untrained misuse of mechanical vibration spell trouble ahead?

> "*shotcrete — concrete placed by a high velocity pneumatic projection from a nozzle.*"
> from ACI Concrete Terminology – CT-18

By definition, the shotcrete process is entirely dependent on high velocity. The velocity and impact force provide the energy required to achieve compaction and consolidation. A skilled crew using proper nozzling techniques can achieve full encasement within fairly dense reinforcement configurations. However, some congested reinforcement patterns may interrupt the flow of material and reduce the velocity before impact. This may reduce the ability to fully encase the reinforcing steel.

Whether cast or shot, the use of larger bars and increased reinforcement congestion presents distinct challenges to attaining full consolidation of concrete during placement. If congestion prohibits the use of internal vibrators with form-and-pour placement, alternative consolidation methods or designs must be considered. This includes use of external mechanical vibration, redesign of the reinforcement, or use of a self-consolidating concrete mixture. With shotcrete placement, such options do not exist.

Currently in structures with congested reinforcement, preconstruction testing (mockups) are used to validate the concrete materials, delivery equipment, and if the shotcrete crew can satisfactorily encase the structural reinforcement (Fig. 1).

Professional nozzlemen who routinely shoot complex mockup panels can immediately identify the exact location of areas within the panel that will be difficult to achieve encasement. Highly experienced shotcrete crews place concrete in these difficult areas through a combination of high-quality shotcrete placement techniques and supplemental consolidation.

TO UNDERSTAND WHY SUPPLEMENTAL CONSOLIDATION MAY BE NECESSARY—THINK LIKE A NOZZLEMAN

For the shotcrete nozzleman, as reinforcement congestion increases, the complexity of placement increases. As complexity increases, so does the potential for consolidation quality to be compromised. It is important to understand that nozzlemen must function within certain natural limitations of the shotcrete process. Nozzlemen must use impact energy derived from velocity as the only means to consolidate the material.

As obstacles between the nozzle tip and the receiving surface increase, the nozzle stream is affected in two distinct ways. Initially, because the nozzle stream cannot be directed into all the shadow areas behind reinforcing bars due to its impeded path, some bars may not receive material at the proper velocity or angle. Larger bars, in conjunction with more restrictive reinforcement patterns, tend to decrease the likelihood that velocity alone can successfully encase and consolidate all the material adequately. Voids can occur within shadow areas behind bars that are within the shadow of other bars. Second, the mixture proportions tend to become segregated by the high-velocity nozzle stream's interference among congested reinforcing bar layouts. Higher quantities of loose, unconsolidated material, or rebounded materials—rather than well consolidated materials—can become embedded, especially within areas that cannot be effectively blown clear with the blow pipe.

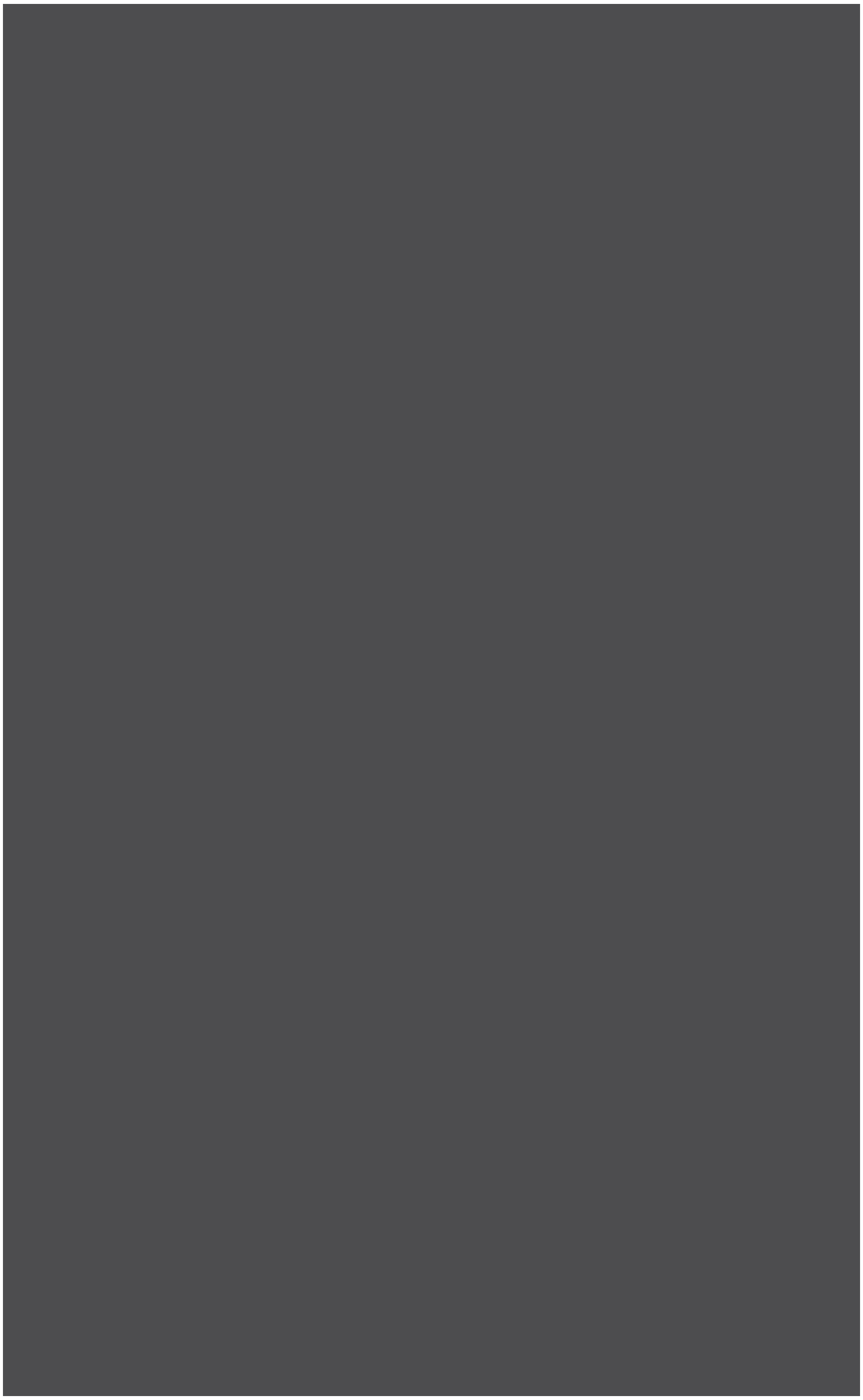
Experienced nozzlemen who direct the nozzle stream skillfully, have proper placement equipment, and use well-chosen concrete mixtures can overcome much of shotcrete's natural limitations. But beyond these, nozzlemen have few additional tools to counteract these limitations. In most instances, the nozzleman is the ONLY person that can make a visual observation of whether acceptable consolidation is occurring during placement. Unfortunately, it is difficult to quantify the degree of congestion that may or may not be successfully encased due to the natural limitations to the process (Fig. 2).

WHAT IS SUPPLEMENTAL CONSOLIDATION?

In heavily congested reinforcing layouts, high-quality shotcrete placement techniques alone may not always assure adequate encasement. Thus, supplemental consolidation should be considered as a method of supplying additional consolidation energy for proper placement techniques. Mechanical consolidation using properly sized concrete vibrators have been incorporated with form-and-pour methods for more than 75 years. However, use with the shotcrete process is not widely known or documented.

Freshly placed shotcrete is highly susceptible to disruption from movements. Experienced placement crews incorporating mechanical vibration in conjunction with shotcrete placement techniques must carefully balance the mechanical energy required to consolidate the material, but not displace it. By comparison, form-and-pour methods use

Fig. 2(a) and (b): Mockup panels with congested to extremely congested reinforcement patterns mechanical vibration as the primary means of consolidation because rigid formwork withstands the material pressures during vibration. With shotcrete—because there are no restraining forms—mechanical vibration, if used improperly, can (and will) interfere with in-place quality. Vibration can unintentionally disturb freshly placed material to the point that delaminations, internal cracks, sags, and fallouts can occur. When vibrators are used with shotcrete, experience, timing, and properly selected equipment will be the determining factor in the success of supplemental consolidation.



UNDERSTANDING MECHANICAL VIBRATION

Concrete vibrators used for form-and-pour methods have not changed significantly for decades. Vibrators use a rotating counterweight encased within a steel body to produce powerful oscillations. As the vibrator is immersed in the concrete, a momentary fluidized puddle of highly agitated material occurs within a small area surrounding the vibrator known as the radius of action. Within the vibrator's radius of action, strong agitation changes the material adjacent to the vibrator to temporarily act in a more viscous, fluidized state, allowing the material to simultaneously release trapped air, consolidate tightly, and potentially segregate.

Manufacturers offer various lengths, exterior diameters, horsepower ratings, and oscillation frequencies to match their intended purpose. Because concrete is a mixture with many components of various weights, vibration can segregate the material as the oscillations cause heavier aggregates to fall and the lighter paste to rise. Heavier high-powered vibrators have a wide radius of action and work well for large elements and coarse mixtures but can quickly segregate material if used improperly. Small pencil vibrators, usually about 1 in. (25 mm) in diameter, are less likely to segregate materials, but have an effective radius of action of just a few inches and may lack the necessary energy to consolidate much more than the smallest element.

The vibrator's oscillation speed or frequency is important to the proper choice of a vibrator. Most common vibrators that plug into 120 or 240VAC household current can only rotate at about 3600 rotations per minute due to the limitations of the available alternating currents' 60-cycles-per-second rate. This low-frequency oscillation speed tends to consolidate concrete material well but unintentionally shakes the mixture's large aggregates downward excessively, causing segregation. As the frequency of the oscillations increase, large aggregates are less (or not at all) affected, so the material's movement is more uniform, diminishing the risk of segregation. This behavior is comparable to the behavior of dental, jewelry, or industrial ultrasonic cleaners, which vibrate a cleaning solvent at very high frequencies. High-frequency oscillations effectively dislodge stains or contaminants but will not shake even the smallest items. Because of the benefits of high-frequency oscillation, many "high-cycle" direct-current or battery-powered vibrators are available and are designed to function at 10,000 rpm or higher.

APPLYING MECHANICAL VIBRATION TECHNIQUES TO SHOTCRETE

With shotcrete, what is the best method to accomplish supplemental consolidation using a vibrator? Because vibration can unintentionally disturb rather than consolidate in-place material, the vibrator's size, frequency, and methodology become far more critical than with other concrete applications. Smaller pencil-style vibrators, which operate at very high frequencies, tend to work best.

Because freshly placed shotcrete can be easily damaged by vibration, the material must be as tightly placed as possible through proper nozzling techniques and the vibrator operated *only* as a means to assist, rather than act as the primary means of consolidation. Consolidation of poorly placed material or low-velocity placement methods using vibration as the primary means of consolidation should not be considered.

Supplemental consolidation requires that the material be carefully placed with vibration only used to help consolidate any remaining smaller voids or shadow areas behind obstacles. Skilled operators focus the vibrator's activity only within these areas, working carefully to avoid movement of the in-place material outside the vibrator's radius of action. If operated carelessly, vibrators will damage in-place work. Because material being vibrated is not retained within formwork, over-vibration **will** cause the fluidized material to flow downward and outward, which can create cracks or delaminations; reduce internal cohesion; or break the bond between the shotcrete, the reinforcement, or the underlying material.

USE TIMING AND VISUAL INDICATORS

The vibrator operator must follow the nozzle closely, move quickly, and continually monitor both the shotcrete's upper bench surface and the areas immediately below the vibrator's radius of action. The operator should be able to recognize the visual indicators indicative of proper shotcrete vibration techniques. The upper surface should become smoother without dropping excessively. The area below the vibrator should flow outward *slightly* without bulging. If vibration is causing excessive movement, or displacing material away from the immediate work area, the vibrator is too large, or the material is being over-vibrated. Work should be stopped, and the problem must be corrected before continuing.

The use of a vibrator as supplementary consolidation of shotcrete can be an extremely valuable tool to counteract the natural limitations of the shotcrete process in congested structural concrete—but only if experienced personnel and properly chosen vibration equipment is paired with high-quality nozzling practices.

Can supplemental consolidation redefine the limits of where shotcrete placement can successfully provide well-consolidated concrete with fully encased reinforcing steel? It already has. Perhaps a future definition for shotcrete is:

> *shotcrete—concrete or mortar projected at high velocity where a combination of impact and supplemental consolidation, when needed, achieve compaction.*

Supplemental consolidation checklist:

- When in doubt whether an element can be successfully shot, ask the nozzleman. Occasionally, the nozzleman is the ONLY person capable of making a visual observation of whether supplemental consolidation may be necessary;
- Gather knowledge on the proper use of a vibrator before purchasing or using a vibrator with shotcrete;
- Choose a vibrator that is best suited for use with the shotcrete process. Small pencil-type vibrators with a frequency range of 10,000 rpm or above work best;
- Use vibration for supplemental consolidation of properly placed shotcrete—not as the primary means of consolidation for low-velocity placement or poorly placed shotcrete;
- Vibrator operator: learn to recognize the timing and visual indicators of proper supplemental consolidation. Follow the nozzleman closely and avoid over-vibration; and
- Nozzleman: learn to identify the visual indicators of proper supplemental vibration techniques. If material sags or becomes visibly damaged from vibration, internal damage from cracks or delaminations are likely; cut it out and replace the entire damaged section rather than simply repairing its surface with a trowel.

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