Can Nozzleman Skill Affect Bond Quality?

By Oscar Duckworth

It is essential that a nozzleman understand how moisture affects shotcrete bond quality. Moisture conditions at the substrate dramatically influence the adhesion of a freshly applied shotcrete layer. A nozzleman must create acceptable saturated surface-dry (SSD) conditions at the substrate if bond quality is required. Shotcrete applied to a clean, roughened concrete substrate in an SSD moisture condition can form a bond that is stronger than the cohesive strength of the underlying layer.

Successful implementation of SSD moisture condition requires an understanding of the properties and behavior of the shotcrete mixture. A qualified nozzleman must possess a fundamental knowledge of these properties.

It is the skill of the nozzleman in executing SSD moisture conditions during placement that will ultimately determine the quality of the shotcrete bond.

- What is the SSD condition?
- How can a nozzleman know when SSD conditions are acceptable?
- What if SSD conditions are not met?
- What is SSD?

SSD describes the best possible moisture condition for an existing concrete, masonry, or stone substrate prior to applying a fresh shotcrete layer. SSD conditions provide necessary moisture to promote acceptable adhesion to the substrate surface.

The nozzleman is the person responsible for establishing SSD conditions. He is the only person who can see these conditions on the substrate as the shotcrete is applied. SSD conditions can be difficult to maintain, and a qualified nozzleman must recognize visual cues that indicate acceptable SSD conditions.

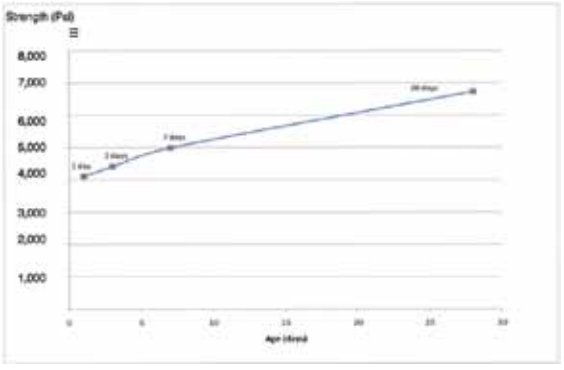

Fig. 1: Shotcrete typical strength gain.
Note: 1 psi = 0.0068 MPa

Impact Energy Affects Bond Quality

A nozzleman must place shotcrete with sufficient velocity. Shotcrete applied at high velocity to a substrate create bonding conditions that are unique to the shotcrete process. Shotcrete mixture particles are sprayed on the substrate at a velocity that can exceed 300 ft/s (91 m/s). Impact energy at the substrate surface effectively embeds a rich, tightly compacted paste layer within the surface irregularities of the substrate. This point of contact between the freshly applied shotcrete paste layer and the substrate surface is referred to as the bond plane. The high-quality paste layer—firmly embedded at the bond plane—is the ideal condition to form a strong bond. Moisture conditions at the bond plane and within the substrate, however, will determine the embedded paste's ultimate bond strength. Adequate hydration of the paste layer is a key factor in achieving bond quality.

Hydration Requires Moisture

Shotcrete does not harden by drying, but by a chemical reaction initiated by portland cement coming into contact with moisture. This reaction is referred to as hydration. The hydration process slowly converts the shotcrete mixture's water/cement paste into a solid structure that binds all of the mixture's separate aggregates together into a single mass. The integrity of chemical bonds formed within the paste is responsible for most of shotcrete's hardened properties.

Hydration requires adequate moisture to develop strong chemical bonds. If there is insufficient moisture within the mixture, hydration cannot occur and the mixture will not gain strength. If adequate moisture is available, the hydration process will slowly generate stronger, thicker crystalline bonds within the paste, and the mixture will steadily gain strength for

approximately 28 days on average (Fig. 1). Adequate moisture within the mixture must be maintained throughout the 28 days for the shotcrete mixture to reach its maximum strength potential.

An Improperly Prepared Substrate Will Stop Hydration

Shotcrete bonding qualities are strongly influenced by moisture levels at the surface and within the existing substrate.

A nozzleman must properly saturate the substrate prior to shotcrete placement. Saturation is required to prevent the existing substrate from absorbing excess moisture from the fresh shotcrete paste at the bond plane. If too much moisture is lost to absorption, and if moisture is not "stored" by saturation within the substrate, hydration within the freshly embedded paste will quickly stop. The low-strength paste will not generate acceptable bond quality. This is why shotcrete will not reliably bond to a dry substrate. SSD conditions require that the substrate be adequately saturated; this means that the substrate will no longer easily absorb water applied to its surface. This may take time, especially in hot, dry, or windy conditions. Specifications often require a constant wet condition for a number of hours prior to placement. The use of sprinklers or a soaker hose can be useful in achieving proper saturation (Fig. 2).

Although moisture is required for hydration, excess surface moisture at the bond plane will reduce bond quality. Much of the quality of the shotcrete product depends on the quality of the mixture's water/cement paste. A paste created with less water will be of a higher quality than a paste containing more water. Relatively small changes in the water volume within the paste can dramatically influence the strength, durability, and adhesion properties of the mixture. When establishing SSD conditions, surface water on the substrate (this will readily transfer to your hand if touched; refer to Fig. 3(a)) will compromise bond quality by increasing the paste's water-cement ratio (*w*/*c*). This will weaken the paste layer at the bond plane, and a weak paste layer will degrade the bond. Excess surface water is a bond breaker. The application of shotcrete to a visibly wet surface should be avoided.

Surface-Dry Condition

After the substrate has been saturated, a surface-dry condition is achieved by allowing the substrate to evaporate back to a damp—but not wet—surface moisture condition. This is easily identifiable by the substrate's dark or green color (the color of fresh shotcrete) and, if touched, will not transfer water to your hand (Fig. 3(b)). SSD conditions only exist for a short time and can be difficult to maintain in hot, windy weather. If the substrate color changes from a dark color back to the light color of dry shotcrete, the SSD condition has been lost. The surface must be rewetted and allowed to evaporate prior to shotcrete placement. The nozzleman must recognize these visual cues to maintain acceptable SSD conditions (Fig. 4).

The ideal SSD condition is attained when the existing substrate is adequately saturated and will

Fig. 2: A soaker hose can be useful in establishing saturated conditions prior to the application of an additional layer of shotcrete

Fig. 3(a): Wall section shortly after saturation. Note its shiny surface; when touched, water is easily transferred to your hand

not absorb excess moisture from the freshly embedded paste at the bond plane. Additional moisture stored within the substrate will allow hydration sufficient time to develop a strong chemical bond to the substrate. The substrate surface must be in a surface-dry condition, free of surface water that will weaken the adhesive properties of the freshly embedded paste. It is only when SSD conditions are met that pneumatically applied shotcrete's natural bond qualities are optimized. Nozzleman skill can affect bond quality. It is the skill of the nozzleman in executing SSD moisture conditions during placement that will ultimately determine the quality of the shotcrete bond.

Fig. 3(b): Wall section in surface-dry condition. When touched, water is not transferred to your hand

Fig. 4: Wall section at left is in SSD condition. Section area at right has lost SSD condition; additional moisture must be applied to right section prior to shotcrete application

Summary

- The nozzleman must possess an understanding of the SSD condition and moisture effect on bond quality.
- The nozzleman is in the best position to ensure that satisfactory SSD conditions are met as shotcrete is applied.
- The nozzleman's skill in implementing SSD conditions during placement is an essential element in achieving high bond quality.

Checklist

- Create good bonding conditions at the substrate. A clean, roughened substrate is required. Cure, form release, or smooth textures on the substrate are bond breakers.
- Use proper nozzle techniques to generate strong impact energy. A good bond requires impact energy.
- Saturation takes time. Plan ahead, use sprinkler or soaker hoses, or allow adequate time to effectively saturate the substrate.
- Rewet as required—SSD conditions do not last. The nozzleman must recognize visual clues to maintain SSD conditions during placement.

References

AASHTO TF37-1, 1998, "Guide Specifications for Shotcrete Repair of Highway Bridges," American Association of State Highway and Transportation Officials, Washington, DC, 122 pp.

ACI Committee 506, 2005, "Guide to Shotcrete (ACI 506R-05)," American Concrete Institute, Farmington Hills, MI, 40 pp.

ACI CP-60, 2009, "Craftsman Workbook for ACI Certification of Shotcrete Nozzleman," American Concrete Institute, Farmington Hills, MI, 126 pp.

*ACI Certified Nozzleman **Oscar Duckworth** is an ASA and ACI member with over 15,000 hours of nozzle time. He has worked as a nozzleman on over 2000 projects. Duckworth is currently an ACI Examiner for the wet-and dry-mix process. He continues to work as a shotcrete consultant and a certified nozzleman.*

Typical bond strength test

Test Number	Core Depth (in)	Core Length (in)	Shotcrete Thickness (in)	Gage Reading (psi)	Applied Force (lb)	Core Diameter (in)	Core Area (in^2)	Tensile Bond Strength (psi)	Failure Mode	Comments
1	2-3/4	2-1/4	2-1/4	1578	818	2.75	5.94	138	50% shotcrete/substrate bond line, 40% substrate, 10% clip	Core contained a wire reinforcing clip impression that may have weakened the bond strength. Bond line appeared relatively smooth (low CSP).
2	2-7/8	2-7/8	2-3/4	4423	2404	2.75	5.94	405	60% shotcrete/substrate bond line, 40% substrate	A few small voids in the shotcrete on the side of core
3	2-5/8	2-1/4	1-3/4	5308	2897	2.75	5.94	488	100% substrate	Shotcrete well consolidated and well bonded to substrate. Core contained wire reinforcing with 1 inch cover
4	2-5/8	2-1/2	2-1/2	3447	1860	2.75	5.94	313	80% substrate, 20% shotcrete/substrate bond line	A few small voids near surface of shotcrete, Core contained wire reinforcing with 1-1/4 inch cover
5	2-5/8	1-1/2	2-1/2	4917	2679	2.75	5.94	451	100 % within shotcrete layer	Failure occurred within shotcrete layer at wire reinforcing. Remainder of core was removed by chipping to determine shotcrete layer thickness. Core contained wire reinforcing with 1-1/4 inch cover.
6	3-0	2	2 +	1832	959	2.75	5.94	162	100 % within shotcrete layer	Failure occurred within shotcrete layer at wire reinforcing. Core contained wire reinforcing with 2 inch cover.
							AVERAGE	326	psi	

Bond strength is commonly measured by coring through the shotcrete layer and into the substrate. A tensile load is applied to the core and it is pulled to the point of failure. The measured load failure divided by the core surface area provides a numerical bond strength. Both wet- and dry-mix shotcrete applications produce very good bond strength, typically 150 psi (1 MPa) or higher.

Note: Do not use bonding agents in shotcrete applications. Bonding agents interfere with shotcrete's natural bonding qualities and can create unreliable bonding.