A BRIEF STATE-OF-THE-ART REVIEW OF PNEUMATICALLY APPLIED CONCRETE OR MORTAR (SHOTCRETE)

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GENERAL DESCRIPTION

Shotcreting is usually classified by designating the process used, i.e., it is either wet-mix or dry-mix and has a fine or a course aggregate.

In the wet-mix process, all the ingredients, including the mixing water, are mixed prior to the introduction of the concrete (or mortar) into the delivery equipment. Accelerators, however, are normally added at the nozzle. The material is jetted from a nozzle at high velocity onto the surface being treated.

In the dry-mix process, the cement and aggregates are thoroughly mixed and fed into the delivery equipment, and the water is introduced under pressure at the nozzle. The concrete (or mortar) is jetted at high velocity onto the surface being shotcreted. However, air-entraining admixtures will not entrain air in a dry-mix shotcrete. The term *gunite* is sometimes used to define the dry-mix shotcrete.

There are advantages to each process. With the wet-mix process, the mixing water can be accurately controlled and thoroughly mixed with the other ingredients, and during the shotcreting operation, there is less dusting and cement loss. In addition, there is less rebounding and material waste in the wet process. When using the dry-mix process, the consistency of the mix can be controlled at the nozzle to meet changing conditions, and start and stop placement characteristics allow for greater flexibility. The dry-mix process is better suited for placing mixes containing light-weight aggregates or mixes requiring high early strength. Dry mixes are capable of being transported over longer distances and are also capable of higher strengths than wet mixes.

MATERIAL PROPERTIES

Properly applied, shotcrete is structurally sound, durable, and has excellent bonding characteristics with other masonry materials. The physical properties are comparable to those of conventional concrete (or mortar) having the same composition. The water-cement ratio for dry-mix shotcrete normally ranges between 0.30 to 0.50 by weight and for the wet-mix it ranges between 0.40 to 0.55. Twenty-eight-day strengths range between 3000 to 7000 psi, although some tests on dry-mix shotcrete have shown strengths on the order of 10,000 psi. Drying shrinkage varies with the mix proportions used, but normally falls in the range of 0.06 to 0.10 percent, which is slightly higher than a low slump conventional concrete. Most shotcrete has a high cement factor and, as a result, has greater potential for developing shrinkage cracks. Wire mesh or reinforcing steel and closer joint spacing are used to control shrinkage cracking. The unit weight and modulus of elasticity of good shotcrete are similar to that for conventional concrete. The freeze–thaw durability of shotcrete is discussed in more detail later.

APPLICATIONS

Shotcrete can be cost-effective 1. where formwork cannot be used, 2. where formwork can be reduced, 3. where access to the area is difficult, 4. where thin layers or variable thicknesses are required, or 5. where normal concreting techniques cannot be used. Shotcrete applications are usually classified as conventional, refractory, or special. Conventional applications employ portland cement, regular aggregates, and ordinary admixtures. Refractory applications use high temperature binders and refractory aggregates. Special applications use proprietary combinations of binders and aggregates or conventional materials with special admixtures.

Conventional shotcrete is used most widely and has been used on new structures, linings and coatings, repairs, and for strengthening and reinforcing existing structures. On bridges, culverts, dams, and other heavy structures, shotcrete is used mostly for repair work. It is also used for strengthening and reinforcing deteriorated concrete beams, columns, slabs, and masonry walls. Refractory shotcrete is used primarily in the refractory industry and is largely used for installing all types of linings.

Special shotcretes often employ admixtures that inhibit corrosion and enhance resistance to chemical attack. Some of the special shotcrete materials include the use of polymer modifiers. These shotcretes are used to repair concrete in highly aggressive environments such as storage bins for storing acids and other caustic materials, chemical spillage areas, ramps, trenches, and pollution control systems. The addition of certain latex formulations to a conventional portland cement shotcrete mix improves flexural and tensile strength, and it may improve the bond and reduce absorption and the penetration of chlorides. A potential application of this material is the repair of concrete bridge and marine substructures and other structures that are subject to chemical attack.

Reinforcement

As a structural material, shotcrete reinforcement is designed using the same criteria as regular reinforced concrete. However, reinforcement should be designed and placed to minimize interference with placement of the shotcrete. Small diameter bars (#5 or smaller) are best used with shotcrete. Exceptional care may be needed to properly incase larger sizes of reinforcing steel in the shotcrete material. Special anchoring devices may also be required to support and maintain the spacing of the reinforcement during the shotcreting operation.

Structural Shotcrete

Shotcrete is best suited to thin, lightly reinforced sections 6-inches thick or less. Where shotcrete is used on heavy structural members in new construction or to bond columns or girders to existing construction, careful planning and forming are required. The nozzle size and rate of feed must be carefully controlled to produce a uniform and dense application. Where possible, columns, for example, should be formed on only two adjacent sides to permit the escape of air and rebound during the gunning operation. Good results can be obtained when three sides are formed provided that the width of the section is at least 1 1/2 times its depth.

Sections containing two layers of reinforcement may require that the first layer be embedded with shotcrete before the second layer is placed. If the layer nearest the nozzle is designed with a reinforcing bar spacing of twelve diameters or greater in both directions, however, satisfactory results can be obtained. Shotcrete should not be used to construct spiral reinforced columns or piling.

FINISHING

1. Dry-Mix: The natural gun finish is preferable because finishing may create cracks, reduce internal cohesion, and break the bond between the shotcrete and the reinforcement or between the shotcrete and the underlying material. Since dry-mix shotcrete is normally stiff and has little excess water to provide for surface lubrication, finishing is difficult and inadvisable.

2. Wet-Mix: Because of the higher consistency of the mix, finishing of a wet-mix shotcrete is easier than finishing a dry-mix application.

When a fine finish or better appearance is desired on either the dry- or wet-mix shotcrete, the initial surface can be left about 1/4 inch low and a final finish applied. The final finish would utilize a shotcrete composed of a fine gradation that passes a #4 sieve, i.e., all large aggregates are removed. This mix would be fairly wet at the nozzle and applied at low volume and under high pressure. The resulting finish would have a stucco-like appearance. This finish could also be floated or troweled if desired.

CURING

Shotcrete should be properly cured if its strength and durability are to be fully realized. Moist curing is considered best, but compounds are satisfactory if drying conditions are not severe and no additional shotcrete is to be applied. Where a gunned finish is to be left, heavier layers of curing compound than is normally used on smooth surfaces should be used.

DURABILITY

Dry-mix shotcrete has been used to rehabilitate structures damaged by freeze-thaw action, chemicals, and fire. Among the structures that have been successfully repaired are bridges, culverts, sewers, dams, docks, reservoir linings, tunnels, tanks, and piers.

Repairs often have to be made within a limited time as in the case of waterfront and offshore structures such as piers. Therefore, the use of set accelerators is often desirable. The use of most accelerators in dry-mix shotcrete can often result in substantial loss of compressive strength, a slower rate of strength gain, and questionable freeze-thaw durability. However, by using a regulated-set cement in dry-mix shotcrete, accelerators are not required, and early age strength development is excellent. Tests (*6*) conducted on dry-mix shotcrete containing regulated-set cement have indicated that:

1. The mean compressive strength after one day was 3900 psi, and after 28 days, it was 5760 psi.

2. After 300 freeze-thaw cycles in fresh water, the specimens displayed excellent moduli of elasticity and relatively low weight loss. Tests in seawater also indicated excellent moduli of elasticity, but mean weight loss was 6.5 percent; thus, for salt water environments subjected to freeze-thaw conditions, this type of shotcrete may require treatment with sealers or coatings or a greater thickness of shotcrete to maintain sufficient cover over the embedded reinforcement.

3. Specimens tested by continuous soaking in both fresh and saltwater indicate that this type of shotcrete has adequate resistance to such conditions.

In other tests (*5*) on regular dry-mix shotcrete sampled from several different contractors, it was found that the material had high compressive strength and good resistance to freezing and thawing in fresh water, but in salt water, treatment with sealers or coatings or thicker cover may be necessary. Additional tests indicated that the shotcretes were relatively impermeable to chloride penetration; thus, they should protect reinforcing steel against corrosion (*5*).

In either the wet- or dry-mix shotcretes, the following factors should be considered in order to produce a freeze-thaw durable shotcrete (*7*):

1. Aggregates susceptible to frost attack should not be used. If marginal aggregates have to be used, the maximum size of the aggregate should be lowered to reduce the susceptibility to freeze-thaw deterioration.

2. Only experienced nozzlemen who can consistently produce homogeneous well-consolidated shotcrete of correct consistency should be used.

3. Shotcrete subjected to saturation at the time of freezing and thawing (marine environments) should have a minimum cement content of 590 lbs per cubic yd and a water-cement ratio below 0.45--preferably below 0.40. In wet-mix shotcrete, this may require the use of water-reducing admixtures.

4. In wet-mix shotcretes, air entrainment is essential. The batch concrete (prior to shooting) should have an air content roughly double that required in place to compensate for losses during the shotcrete application process.

5. High compressive strength does not result in adequate freeze–thaw durability without an adequate air void system. However, an air void spacing factor greater than the 0.20 mm recommended by ACI for regular concrete can be permitted for high quality shotcrete. At water–cement ratios of 0.40 or less, a spacing factor of 0.30 mm can provide adequate durability.

6. Where freezing and thawing in a saturated condition is expected, preconstruction testing should be conducted to assure that the shotcrete materials, equipment, and crew can produce the material with the water–cement ratio, air void content, and compressive strengths required.

More recent tests (*8*) (which were incomplete at this writing) have utilized a 7.5 percent addition of silica fume for improving the durability of dry-mix shotcrete. Freeze–thaw durability, permeability, and strength were all improved by the addition of silica fume. Based on information currently available, the addition of silica fume can improve the durability of both wet and dry shotcrete mixes.

SHOTCRETE FAILURES

Most failures have been found to be related to poor preparation of the substrate surface to which the shotcrete is applied. Application of a thin layer of shotcrete to a poor durability substrate usually results in continued deterioration below the shotcrete. Alkali–aggregate reactivity in the substrate concrete, for example, could cause the shotcrete to peel off unless it is reinforced and anchored deep into the substrate material. Failures can also occur where drainage and pressure relief are not provided in applications where substantial water pressure can build up behind the shotcrete. Failure to clean spray and loose rebound material from the surface of an existing shotcrete layer prior to application of the next layer can cause delamination in the presence of water and pressures from freezing and thawing. This is particularly a problem when latex-modified shotcrete is used because water can severely degrade the bond between layers. To minimize the overall potential for debonding, a relatively impermeable shotcrete is required in repair applications.

SPECIFICATIONS AND CONTROL

Specifications for the materials and some of the equipment used in normal shotcreting operations are covered by standard ASTM and ACI methods and procedures. Specifications for materials, proportioning, and application of shotcrete are given in ACI 506.2–83 (*3*). However, there is a shortage of engineering data that can be used to aid in the control of the product. There are a lack of standard testing procedures, and there is difficulty in correlating factors between test specimens and the in-place shotcrete. Part of the problem can be attributed to the widely varying application techniques and to variations in material quality and gradation.

The question of exit velocity at the nozzle is important because it is believed that this has an effect on the quality, strength, and durability of in-place shotcrete (*8*).

Very early tests have shown that shotcrete strength increases with exit velocity up to an optimum level. In addition, smaller nozzles tend to achieve optimum strengths at lower velocities than do larger nozzles. In a review of the various studies that have been conducted, Glassgold (*8*) concluded that there was no consensus on nozzle velocity and felt that research is needed to determine whether there are interrelationships between velocity and durability. Glassgold also questioned whether there are rotary guns being used that produce nonuniform discharge, which results in a nonhomogeneous and variable dry-mix shotcrete material. He suggested that a long nozzle, reduced chamber size, and increased frequency of chamber discharge can help reduce the problem but questioned if all applicators understood the problem or took the effort to make the adjustments.

Control of the overall shotcrete operation is important since the quality of the product is contingent upon surface preparation, mixing, material quality, the application equipment, and the experience of the applicators (*4*).

OTHER DEVELOPMENTS

As new equipment and techniques and the development of new materials have evolved, the use of shotcrete has found wider application. Improvements in accelerating admixtures, the use of steel fibers, and the use of remote and robotic devices have spread the use of shotcrete in tunnel construction (*1*, *2*). The use of short fibers of steel in the material has gained favor since the fibers improve flexural and shear strength and impact resistance. Special care and equipment may be necessary to prevent clumping of the fibers and to ensure proper proportioning. However, research still needs to be done in this relatively new application. The optimum size and shape of the fibers and their method of addition to both the wet- and dry-mix shotcretes, for example, were not well known by the mid-1980s.

The *1987 ACI Manual of Concrete Practice* (*1*) lists future areas of research and development as:

1. rational shotcrete design
2. nozzle design
3. in-place testing techniques
4. materials
5. equipment mechanization
6. substrate evaluation
7. process automation.

SUMMARY

Shotcrete that is applied using quality materials can provide a suitable product with good durability. The major elements involved in obtaining a high quality product are design, quality control, quality materials, proper application equipment, craftsmanship, and placement technique. However, there is a shortage of engineering data, a lack of standard testing procedures that directly relate to the finished product, and there is incomplete knowledge of how nozzle design and exit velocity relate to the durability of the finished product.

While there are a number of examples of shotcrete failures, there is a general consensus that good quality shotcrete is a durable material even when used in severe environmental situations. Some special precautions for the use of shotcrete in severe environments as well as notes on finishing, curing, and reinforcement are given in this review.

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