PAPER NO. 1 Defines both wet-mix and dry-mix shotcrete, and reports on its generally satisfactory performance in widely varied applications. Shotcrete is well adapted to thin, lightly reinforced concrete sections in new construction, as well as for repairs and thin overlays. In spite of a high cost per cubic yard, it is frequently more economical than conventional concrete for such purposes.

Results of the Committee 506 questionnaire sent to shotcrete users are reported, including data on extent of use, performance, and causes of unsatisfactory performance. Poor workmanship is the most frequently reported cause of shotcrete failures. Noting that sampling and testing procedures must be quite different from those for conventional concrete, emphasis is placed on test sections gunned under field conditions.

Shotcrete as a Construction Material

By T. J. READING

■ ONE OF THE ATTRACTIVE PROPERTIES of *conventional concrete* is its ability to be molded into any shape, simply by placing it in a form of the required shape. *Shotcrete* permits even simpler construction since all that is required is a backup surface consisting of a light form; sometimes no form at all is required. When we also consider that only a small, portable plant is required for applying shotcrete, this method of construction offers considerable appeal for many thin sections.

Shotcrete has been referred to as gunite, pneumatically applied mortar or concrete, sprayed concrete, and by other terms. It is defined as mortar or concrete which has been conveyed from the delivery equipment (generally called the gun) through a hose and pneumatically projected at high velocity onto a surface. The force of the jet impacting on the surface compacts the material. A relatively dry mixture is generally used so that the material is capable of supporting itself without sagging or sloughing, even for vertical and overhead applications.

The two basic shotcreting processes are:

1. The widely used dry-mix process, where a mixture of cement and damp sand is conveyed through the delivery hose to a nozzle where the remainder of the mixing water is added

2. The recently introduced wet-mix process where all of the ingredients (including water) are mixed before they enter the delivery hose.

While the gunning equipment and some of the procedures are different, either method will produce a quality of shotcrete suitable for normal requirements.

USES OF SHOTCRETE

Shotcrete is well adapted for thin, rather lightly reinforced sections in a variety of new construction. This includes such structures as roofs—particularly curved or folded sections (Fig. 1-1)—certain walls, canal and tunnel linings, swimming pools, and prestressed tanks. It is also widely used for:

1. Thin overlays over concrete, masonry, steel, and certain other materials

2. Repairing deteriorated concrete and concrete damaged by fire or earthquake

3. Stabilizing rock slopes (see Fig. 1-2), and providing temporary protection against air slaking or raveling of freshly

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excavated rock surfaces which will be later covered with concrete

4. Refractory linings and encasing steel for fireproofing.

Shotcrete is not generally recommended for heavy sections because of the rather low placing rate (generally 1 to 8 cu yd per hr per gun), the rather high per yard cost in place, the difficulty in assuring a good quality material in place particularly where the section contains considerable reinforcement, and because the relatively high cement factor may not be desirable. Also, it cannot be successfully applied in tight places and closed areas where there is not room for proper manipulation of the nozzle, or where the dust accompanying the application is objectionable.

Merits of shotcrete as an overlay material

There are sound reasons why shotcrete is our best portland-cement-based material for making thin overlays or repairs to new or old concrete. When the mixture leaves the nozzle at high velocity and strikes the hard surface which is to be repaired or covered, the coarser particles ricochet (rebound) from the surface. This leaves an excellent bond coat of fine grout, in intimate contact with the surface because of the high velocity of impact. After a thin layer of the grout has been built up, it acts as a cushion to reduce the percent of rebound during the ensuing buildup. The composition of the bulk of the cross section should not be greatly different from that which left the gun.

This good initial bond is preserved because of the virtual absence of bleeding for the stiff mixes used in shotcrete. (In conventional concrete overlays, bleeding is a problem for vertical and particularly for overhead work.)

When using shotcrete for repairs the engineer should not expect miracles, however. A permanent repair is not likely where a thin shotcrete coating is applied over deteriorated concrete in a cold climate. In such cases the old concrete continues to deteriorate at the bond plane (perhaps aggravated by moisture penetrating through fine cracks in the shotcrete), and the shotcrete coating generally comes loose from the base concrete within a few years.

It is therefore highly important that all unsound material be removed if at all possible before applying shotcrete. Improper preparatory work is responsible for more failures in shotcrete repair work than any other single factor. The final cut surface should be critically examined to see that it is sound and properly shaped.

A liberal application thickness, 1½ in. or more, and inclusion of wire mesh in the repair are generally advisable. A high quality of shotcrete is also important in repairs to insure good bond, good durability, and minimum shrinkage.

COMMON MISCONCEPTIONS REGARDING SHOTCRETE

There have been a number of popular misconceptions about shotcrete because this is a specialized process (differing greatly from normal concreting procedures) which not many engineers have studied; because certain terms used in the shotcrete industry have not meant the same thing as when used in conventional concrete work; and because knowledge has been lacking in some areas.

As additional information is disseminated, these misconceptions are being gradually cleared up. Designers are therefore becoming less reluctant to specify shotcrete where it is appropriate, and the user is getting greater assurance of a good field application. It is hoped that the following information and discussion will help to clear up certain areas which are still frequently misunderstood.

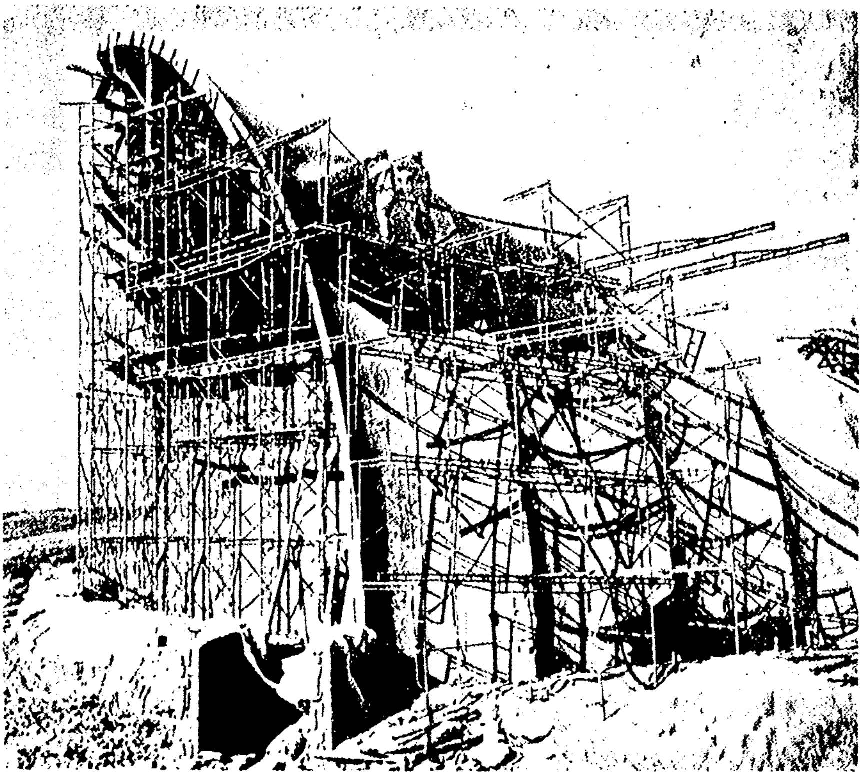
Meaning of "hydration"

Although not used in "Recommended Practice for Shotcreting (ACI 506-66)," the term "hydration at the nozzle" is frequently employed in the shotcrete industry. This simply means an intimate mixing of the water added at the nozzle with the cement-sand mixture which has passed through the hose (in the dry-mix process). The concrete engineer finds this use of the word "hydration" confusing since he has been taught that hydration is a chemical reaction between the cement and water which starts at the time of mixing and continues over a period of years.

Rebound and its effect on shotcreting

The shotcrete mixture leaves the nozzle at a very high velocity, hundreds of feet per second. When it strikes the application surface —generally 3 to 4 ft away—a considerable percentage of the material ricochets or rebounds from the surface. This rebound consists mainly of the coarser particles of sand and much of the coarse aggregate when such is included in the mix. The rebound will vary from about 10 to 50 percent of the material leaving the gun, the actual amount depending on the grading and proportions of the mix, the consistency, the velocity of impingement, and other factors. The percent of rebound will be much higher when gunning an overhead surface than when gunning down onto a floor or slab.

Because of rebound, the shotcrete in place is richer than the mixture which leaves the gun. Trapped rebound, if not removed,



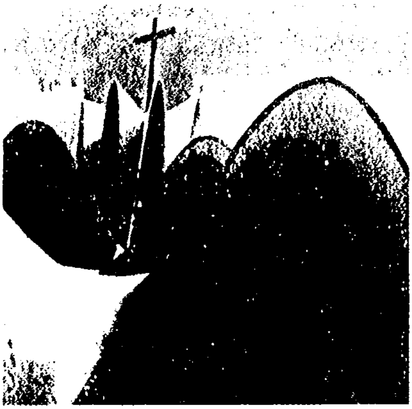


Fig. 1-1 Use of shotcrete in thin shell roof construction, showing a detail of a completed roof in the lower picture at the right

also causes sandy, porous areas and laminations in the cross section which are a great detriment to shotcrete quality. With the stiff mixes used in shotcrete and the high velocities necessary for good compaction, some rebound is inevitable. However, high percentages of rebound should be avoided if possible because of the tend-

Fig. 1-2 Shotcrete can readily be placed in many locations virtually inaccessible for conventional concreting. One example is this rock stabilization work.

ency to produce undesirably rich mixes in place, the problem of keeping rebound out of the work (especially in reinforced sections), and the waste and resulting cleanup which will be required.

Water-cement ratio

Widely different values are quoted for the water-cement ratio of shotcrete. It is sometimes said to be very low, of the order of 3 gal. per sack of cement (0.27 by weight) or less. The concrete engineer knows how extremely dry such mixtures are and wonders how they can be adequately compacted. He further knows that this amount of water is insufficient to chemically hydrate all of the cement. Apparently some of these low reported values include only the water added at the nozzle, which is difficult to measure at best, and ignores free moisture in the sand which generally ranges from 3 to 6 percent. Some other data derived from testing shotcrete in place have been disputed because of a question as to the accuracy of the determinations of water and cement content, particularly the latter. Most reliable data indicate the water-cement ratio of good field shotcrete to be in the range of 4 to 5.5 gal. per sack (0.35 to 0.50 by weight). It is important that the shotcrete be wet enough for the placing conditions to obtain good compaction and reduced rebound. On the other hand, the water content should not be higher than necessary because sloughing of the fresh shotcrete may result, and because the quality of the hardened shotcrete will be poorer (especially from the standpoint of drying shrinkage).

Shotcrete compared with conventionally placed concrete

Is shotcrete superior to ordinary mortar or concrete of the same proportions, as is sometimes claimed? There seems to be adequate data to prove that the strength and other properties of shotcrete are the same as those of conventional mortar or concrete of the same proportions and void content. The strength of shotcrete applied under favorable conditions should be high, but so also is the strength of rich, low slump, well compacted conventional mortar or concrete. On a recent Corps of Engineers project, some newly applied shotcrete was scraped from the surface and rammed into conventional 6x12-in. cylinder molds. The 28-day strength was found to be over 7000 psi, slightly higher than that obtained on sawed specimens from shotcrete panels. The advantages of the shotcreting process are that it is a convenient and economical means of applying such material in a variety of construction, and it is capable of building up an excellent bond coat.

Coarse-aggregate shotcrete

Now that equipment is available for gunning *concrete,* will the use of mortar mixes soon be outmoded? *Wet-mix* delivery equipment is now available for gunning mixes containing aggregate graded up to about ¾ in., although the percentage of coarse aggregate is generally considerably less than for conventionally placed concrete. There have also been encouraging reports from Europe and South America on gunning concrete containing aggregate graded up to about 1 in. by the *dry-mix* process, and a limited amount of experimentation in this field is being carried out in the United States.

There is a definite place for gunned *concrete* in construction, in the heavier sections where it promises economy and sometimes improved quality through a reduction in cement content. The use of coarse aggregate (especially pea gravel sizes) in shotcrete is increasing. However, the following points should be kept in mind:

1. Most shotcrete applications today are in very thin sections where mortar mixes are more suitable.

2. A stiff, sound, well compacted mortar is a good construction material in its own right for thin sections. A number of recently published studies on the effect of maximum size of aggregate on the properties of concrete have shown that the advantages of having coarse aggregate in the mix may not be as great as engineers formerly assumed.

3. Adding coarse aggregate to the mix will increase the rebound and waste, and the ricocheting coarse aggregate may make it more difficult (particularly in reinforced sections) to attain the primary objective—*sound* shotcrete.

QUALITY CONTROL TECHNIQUES

How do sampling and testing of shotcrete compare with that of conventional concrete? There are great differences. In conventional concreting it is customary to send the materials to the laboratory where they are mixed and specimens are molded. One can reasonably expect the quality of this concrete to be closely duplicated later on the construction project. This is not necessarily the case with shotcrete. Here the most important factors affecting quality are the field factors—the conditions under which it is placed, the equipment used, and especially the competence of the application crew. On one Corps of Engineers job the compressive strength of shotcrete was increased from 1500 to 6000 psi merely by changing from an inexperienced to an experienced crew (see Fig. 1-4). So if test results are to be meaningful the specimens must reflect the workmanship in the field as well as the proportions of the mix.

In the past the usual control test specimen has been a 6x12-in. cylinder made by gunning the mixture into a mold constructed of hardware cloth. Unfortunately such specimens are generally not representative of gunned sections and there have been many instances where the quality of shotcrete in these cylinders bore no similarity to the quality in the structure. Sometimes, because of a lack of understanding of the principles involved (especially the effect of rebound) in gunning mortar or concrete into place at high velocity, even poorer practices have been permitted: gunning into conventional cylinder or beam molds; strengthening hardware cloth molds with sheet metal bands to insure roundness; or casting cylinders (in the wet-mix process) from material before it enters the gun. In such cases the results have been extremely misleading.

The only reliable determination of the quality of shotcrete in place is obtained by taking samples from a typical gunned section. Cores from the actual structure are to be preferred. However, this would generally be costly, and may be undesirable or impracticable. The next best solution is to use, for the bulk of the testing, test panels gunned under field conditions. They are very useful at the beginning of the job to verify that the application crew can produce the required quality of shotcrete using the equipment, materials, and mix proportions proposed for the job. Small test panels should

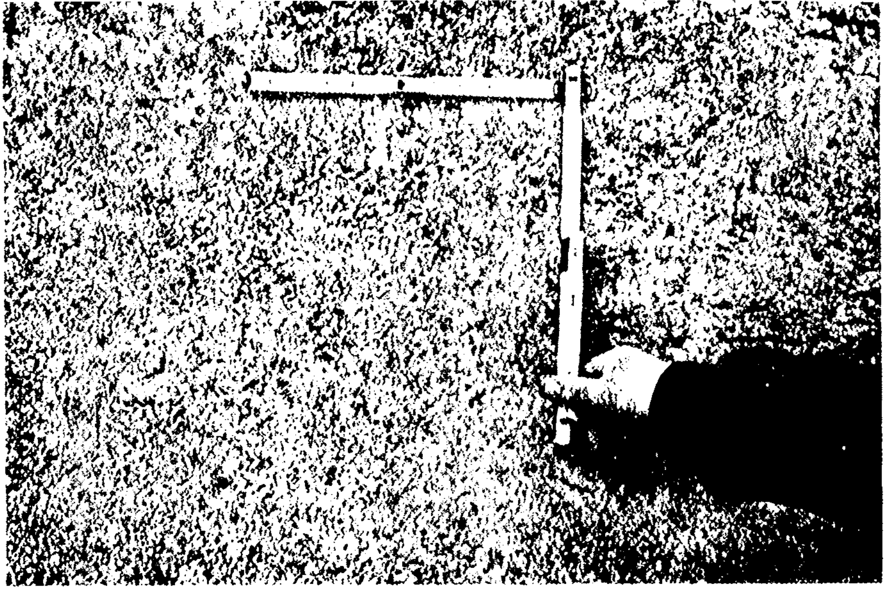


Fig. 1-3 Repair to lock wall in northern Michigan. Shotcrete in excellent condition after more than 25 years of severe exposure

also be periodically gunned for control tests. Specimens are cored or sawed from the panels for testing.

Because of their simplicity, cylinders may be used for day-to-day control on small jobs where the results appear to correlate with results from test panels or cores from the structure, and provided their limitations are understood.

The shotcrete inspector should systematically sound each layer of shotcrete in the structure to look for areas of drumminess (poor bond) or other evidence of poor quality. Occasional cores should also be taken from the structure to assure that the results of the control tests are valid.

RESULTS OF QUESTIONNAIRE ON SHOTCRETE

When ACI Committee 506 undertook to revise ACI Standard 805, "Application of Mortar by Pneumatic Pressure," published in 1951, the members soon discovered that there was considerable difference of opinion on the merits of shotcrete as a construction material, and on proper application procedures. The committee therefore undertook an exhaustive search for all available information on the subject.

A questionnaire was circulated to most (about 30) of the largest users of shotcrete on the continent, including federal, state, and municipal agencies; private power companies; and consulting engineers. The questionnaire requested information on extent of use, performance, causes of unsatisfactory performance, test data and recommendations on testing, and cost of shotcrete. All addressees replied and most went into considerable detail. A summary of the replies is given below.

Extent of use

The survey indicated that shotcrete has been used in the following types of construction:

> Certain types of thin walls; domes and thin shells; columns in tilt-up construction; warped inlets and outlets to culverts; swimming pools; lining ditches, canals, and flumes; lining levees and sloping walls of reservoirs; tunnel lining
>
> Slope stabilization and erosion protection; protective coating over rock applied immediately after excavation to prevent air slaking and raveling prior to concreting (especially in tunnels); protective coating over prestressing wire in concrete tanks; protective coating over steel pipe; lining coal bunkers, gas ducts, and steel stacks—generally for the purpose of preventing corrosion; refractory linings; fireproofing; other types of new construction where conventional methods are either ineffective or uneconomical
>
> Repair of buildings and concrete chimneys; repair of hydraulic structures, piers, bridges, channel and tunnel linings, culverts, and wharf structures; bonding layer for conventional concrete repairs; and to give rough surface texture where such is desired.

It is believed that, with the exception of swimming pools, the replies cover most of the shotcrete construction on this continent.

Performance of shotcrete

In general, these users consider shotcrete suitable for the uses listed above. Most believe that, if proper materials and mix proportions are used and the mix is properly applied, the strength and durability of shotcrete are equal to or superior to conventional concrete for thin elements. Several examples of outstanding durability were cited. Shotcrete landing barges have been in service in sea water since 1919. Extensive repairs made in the late 1930's to lock walls in northern Michigan (Fig. 1-3) are still in excellent condition in that cold climate. On the other hand some have not had good experience with shotcrete, particularly in severe exposures.

Most of the users prefer not to use shotcrete for members more than 3 or 4 in. thick, especially where there is considerable reinforcement, because of the danger of trapping large quantities of rebound. A few also believe that the numerous layers required to build up heavy sections may create undesirable shrinkage strains which are harmful to bond, especially in long sections.

Practically all commented favorably on the ability of shotcrete to bond to concrete, masonry, and steel surfaces. Experience has also