

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 pre-stressed 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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Mr. Reading is a member of the ACI Board of Direction and chairman of ACI Committee 506, Shotcreting, and Committee 309, Consolidation of Concrete. He also serves on ACI Committees 201, 302, and 531, and is a member of ASCE, ASTM, the National Society of Professional Engineers, and the U. S. Committee on Large Dams.

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,

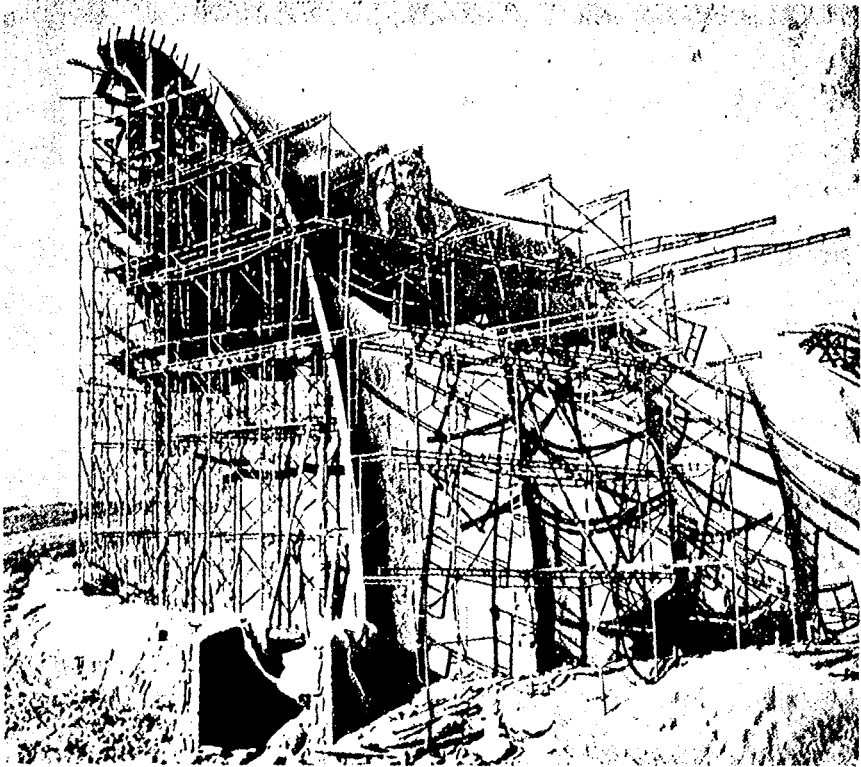
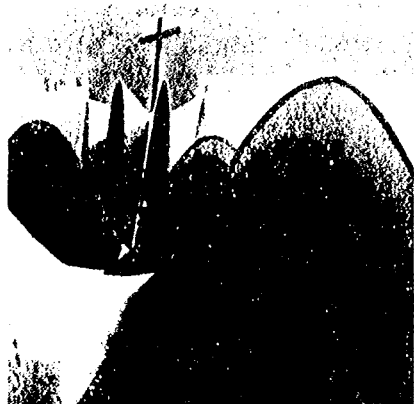


Fig. 1-1 Use of shotcrete in thin shell roof construction, showing a detail of a completed roof in the lower picture at the right



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 $\frac{3}{4}$ 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

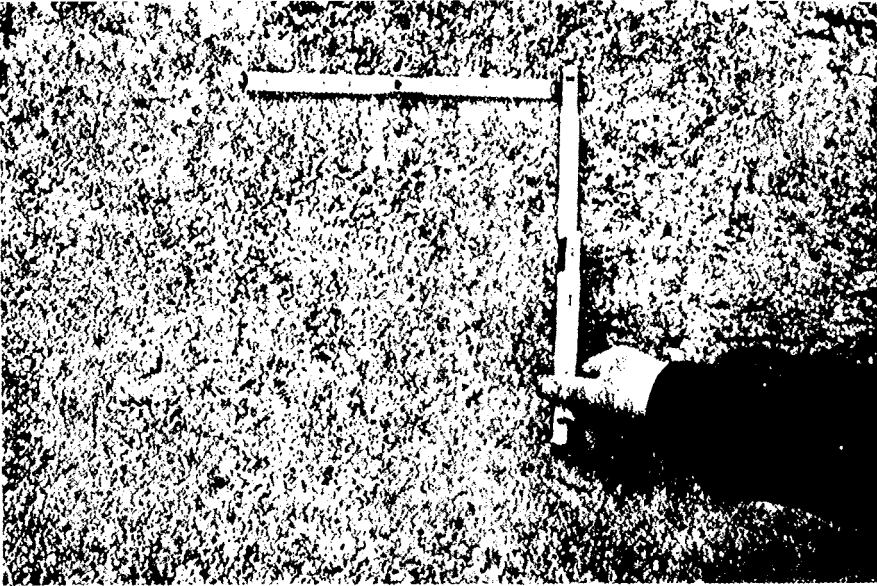


Fig. 1-3 Repair to lock wall in northern Michigan. Shotcrete in excellent condition after more than 25 years of severe exposure

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

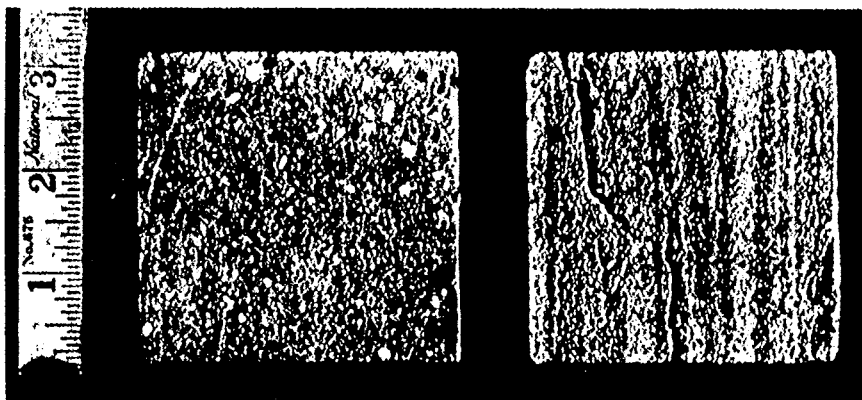


Fig. 1-4 Effect of workmanship on quality of shotcrete. Cube on right is from panel made by inexperienced crew and contains laminations and porous areas; compressive strength was 1500 psi. Left cube, from panel made by an experienced crew, had a compressive strength over 6000 psi. Same mix and gunning equipment were used for both panels.

generally been good where shotcrete has been bonded to rock—for stabilizing and protecting rock surfaces from erosion, and preventing air slaking and raveling.

There were a few complaints of excessive cracking (due to a greater shrinkage factor than conventional concrete) where shotcrete has been used for long continuous walls. The result was poor appearance and leakage.

A few questioned whether shotcrete can be depended upon for long-time protection against corrosion when applied as a cover coat over prestressing wire, because of the likelihood of some cracks and sand (rebound) pockets.

Where shotcrete has been used to repair deteriorated concrete in hydraulic structures in severe climates, its record has been only fair. In several cases it was admitted that the preparation of the old surface left something to be desired. Also it is generally agreed that it is hardly fair to compare the performance of a 2-in. veneer of shotcrete with that of a much thicker (frequently 6 in. or more) and much more costly conventional concrete repair.

In many cases shotcrete is applied to nondurable concrete surfaces with the expectation that the repair will have a relatively short life, because the economics are so favorable as to allow frequent repair by this method. This life can sometimes be prolonged by applying a sealer to the surface to inhibit entry of water through fine cracks and porous areas, if there are such, in the shotcrete.

Causes of failures

Poor workmanship was cited by these users as being the principal cause of failure. Most of those who are not satisfied with the field performance of shotcrete reported that the work was sometimes done under inadequate supervision and without qualified craftsmen (see Fig. 1-4).

Causes of the failures, in three classifications according to frequency, are listed below:

Most common causes

Improper preparation of old concrete surface in repair work (especially failure to remove sufficient deteriorated concrete to insure bond with sound concrete). With the continued deterioration of the old concrete, the shotcrete layer (itself essentially intact) comes loose.

Failure to clean rock surfaces adequately

Sagging (sloughing) of shotcrete during application

Inclusion of trapped rebound in shotcrete section (Fig. 1-5)

Less common causes

Applications too thin to perform satisfactorily. (One agency got poor performance from canal linings $\frac{3}{4}$ to $1\frac{1}{2}$ in. thick but has had good results since the thickness was increased to 2– $2\frac{1}{2}$ in.)

Reinforcement not adequately designed or not properly placed in the field; for example, too close spacing of the reinforce-

Fig. 1-5 Trapped rebound behind reinforcing bars weakened these sections and caused cracks in formed surface. Nozzleman did not use proper technique for encasing the bars in this thick wall (see Fig. 606 [a] on p. 211).

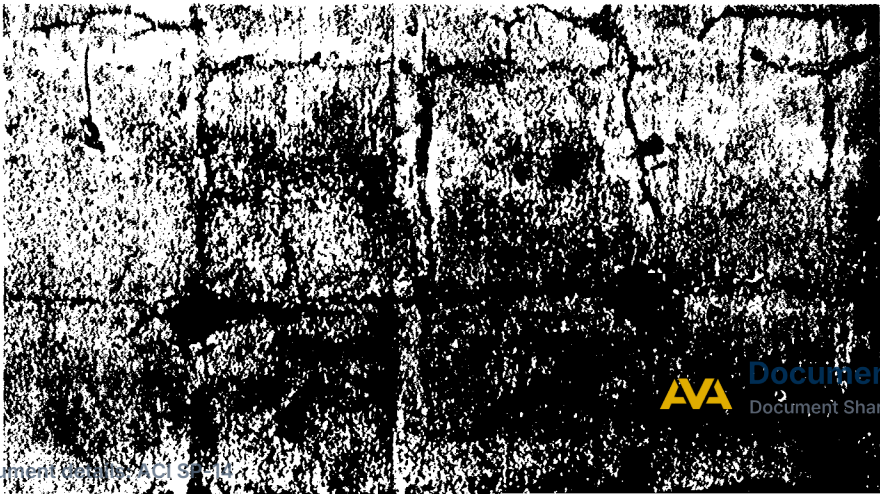




Fig. 1-6 Congested reinforcement is the principal cause of the sand pockets and porous areas shown here. Such design and placement of reinforcement is not recommended even for conventional concreting; in shotcrete construction it is impossible to get sound material between and behind the bars.

ment (especially at laps) to permit nozzleman to get proper embedment (Fig. 1-6)

Insufficient wet curing

Uncommon causes

Poor materials

Mix too rich

Mix too lean

Nonuniform feed to nozzle, causing variation in consistency of material as applied (dry-mix process)

Water not intimately mixed with other ingredients (dry-mix process)

Too much finishing

Rough surface texture, which is occasionally objectionable

Inadequate equipment, especially insufficient compressor capacity

Suspected high permeability of shotcrete. (While test data available to the committee indicate very low permeability, about the same as for good quality concrete, occasional reports are received from the field that shotcrete is porous. Where this is caused by a layer of rebound left on the surface there is no cause for concern, but where much of the cross section is porous the condition is more serious).

One firm stated that the real underlying cause of poor shotcrete is inexperienced designers, contractors, and inspectors—people ignorant of the facts in producing good shotcrete.

Data and recommendations on testing

As expected, it was found that reliable test data on shotcrete is rather meager. Compressive strength tests have generally been made on cylinders prepared by gunning the mixture into 6x12-in. wire basket molds, as required by ACI Standard 805-51 (now superseded by 506-66, reprinted on p. 193). Most reported 28-day strengths are in the range of 3000 to 7000 psi, using mix proportions from 1:3½ to 1:4½. Where cores have been taken from structures the strength values have generally not correlated satisfactorily with cylinder tests.

One agency which uses considerable shotcrete as a structural material for rehabilitating buildings took about 60 cores from several jobs. While the average strength was comfortably over the required 3000 psi, there was a rather large variation in strength, and a few values were very low. The low strengths were found to be caused by rebound lenses or pockets behind the reinforcing bars or laminations following the shooting angle. This agency concluded that wire basket specimens have little correlation with the quality in the structure.

About two-thirds of those replying, including almost all who use shotcrete as a structural material, expressed a similar view with respect to shotcrete cylinders. They favor test panels and/or cores from the structure.

About a third favored continuing to use cylinders for control testing, although some would change the method of casting, and one user stated that cylinders should not be used unless the results have been correlated with core tests.

Several replies commented that the search for simpler, more reliable methods of checking the quality of shotcrete should be continued.

Cost

The costs reported for shotcrete in place are in the approximate range of \$60 to \$150 per cu yd (including forming and reinforcement), depending on the type and size of application, scaffolding requirements and other factors. In spite of this rather high cost per cubic yard, shotcrete is frequently cheaper than conventional concrete for thin sections. The economy results from the greatly reduced forming requirements, reduced volume of material required when coating rough terrain (slope stabilization, for example), and the simple plant requirements. Generally shotcrete can compete with conventional concrete for thicknesses up to about 3 in., although it is occasionally economical for thicknesses up to 6 in. or more.

PAPER NO. 2 Describes the techniques of dry-mix shotcreting. Cements and aggregates for shotcrete are reviewed. Basic types of equipment manufactured in the United States are discussed, and their operation is explained, including details of the nozzleman's work. Sand pockets are defined, and reasons for avoiding such imperfections are given. Recommendations on the use, size, and proper encasement of reinforcing steel are made.

Bonding ability, curing, finishing, and acceptable weather conditions for shotcreting are considered. Comments are given regarding compressive strength testing and qualification of nozzlemen.

Dry-Mix Shotcrete Practice

By THEODORE R. CROM

■ IN 1910, EQUIPMENT FOR PNEUMATICALLY applying a sand-cement mix was first introduced to the public by the Cement Gun Company of Allentown, Pennsylvania, at the Cement Show in Madison Square Garden, New York. In 1912, the name "gunite" was coined by the firm to denote pneumatically applied cement-sand mixes. For years that company was the sole manufacturer of pneumatic placement equipment. However, the wide acceptance of gunite or pneumatically placed mortar and the entry into the field by different equipment manufacturers has led to the adoption of a different term, "shotcrete," to describe the process. As used by ACI, "shotcrete" includes both a dry mix transmitted pneumatically through a hose and a wet mix transmitted through a hose, either pneumatically or by positive displacement pumps, and jetted into place by air at high velocity. This paper deals only with dry-mix shotcrete, although some of the principles apply to wet-mix shotcrete as well.

SHOTCRETING EQUIPMENT

Manufacturers

Available on the market today are several types of equipment for the spray application of dry sand-cement mix, occasionally including some small coarse aggregate. The Allentown Pneumatic Gun

Company, Allentown, Pennsylvania, successors to the original Cement Gun Company, still manufactures an excellent shotcrete placement machine. The equipment produced today is quite similar to that manufactured by them over the past fifty years.

Equipment of somewhat similar operation is also manufactured by the Air Placement Equipment Company of Kansas City, Missouri, and Ridley and Company of Los Angeles. Both of these firms produce, in addition to the gun, a total unit which includes elevators, mixers, dryers, and other allied equipment. The former firm produces equipment for both wet-mix and dry-mix placement. Engineered Equipment, Incorporated, in Waterloo, Iowa, manufactures a gun that is continuously fed through a single hopper instead of being intermittently fed to the top chamber of a double-chamber system as is more common.

Equipment components and operation

The equipment required for a minimum shotcrete operation consists of the gun, an air compressor, material hose, air and water hoses, nozzle, and sometimes a water pump (see Fig. 2-1). Miscellaneous small hand tools and wheelbarrows are also required. With this minimum equipment one can accomplish shotcrete work satisfactorily.

To assure a constant flow of water of satisfactory pressure, most good shotcrete equipment includes a water pump of piston, gear, or centrifugal type. If the piston pump is used, it should feed into a receiver tank to eliminate pulsation of water at the nozzle.

Since his father was a pioneer and innovator in the field, **Theodore R. Crom** literally grew up with shotcrete. An experienced onetime professional gunman and nozzleman, Mr. Crom also has a BS degree in civil engineering and is a registered engineer in Florida, California, and other states. President of the Crom Corporation, Gainesville, Florida, since 1953, he is responsible for the design and construction of 30 to 50 prestressed, composite shotcrete tanks every year.

Mr. Crom, who has written several articles on shotcreting, regularly spends time in the field, training and working closely with six or eight company crews in actual shotcrete application. He is an ACI member and serves on the Institute's Committee 344, Circular Prestressed Concrete Structures, and Committee 506, Shotcreting.

Modern high-production equipment includes considerably more investment in elaborate elevators, mixers, batchers, and associated equipment. Total investments for a single unit can quickly reach \$30,000 to \$50,000 for high production. With the minimum equipment listed above, one can get by at about \$15,000 or on a rental basis for much less.

The normal flow of material in a shotcrete operation follows a standard pattern for all types of equipment. First, the materials must be batched, usually in quantities of approximately 94 lb of cement to 400 lb of sand. Batching equipment may be sophisticated and automatic, or as rudimentary as so many wheelbarrow loads of sand per bag of cement. Quantities are controlled both by volume and by weight, although the weight method is normally considered superior. After batching, the mix is prepared by a paddle, turbine, or drum mixer, and in some cases by a screw mixer or conveyor.

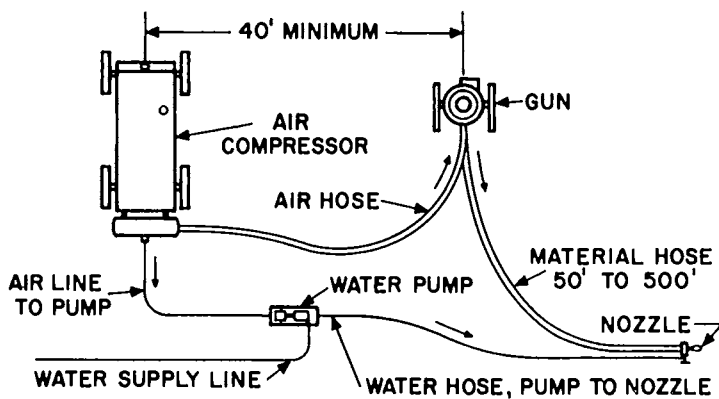


Fig. 2-1 Typical arrangement (plan view) of equipment for shotcreting

The mixed material is carried in suspension by compressed air through a hose to the nozzle. At the nozzle, water is injected into the material in a number of fine streams. As the material passes through the final 10 or 12 in. of the nozzle, it is mixed with the water. Mixing continues as the stream of material and water passes between the nozzle and the point of impingement. Upon impact, water mixing is complete.

In one type of equipment the material is premixed in a paddle mixer, elevated, and final-mixed in a combined paddle-screw mixer before dropping into the gun. During or after mixing, material is elevated by a belt conveyor, screws, or bucket elevators to an overhead hopper. From the overhead hopper it is dropped by gravity into the top of the double-chamber gun (Fig. 2-2).

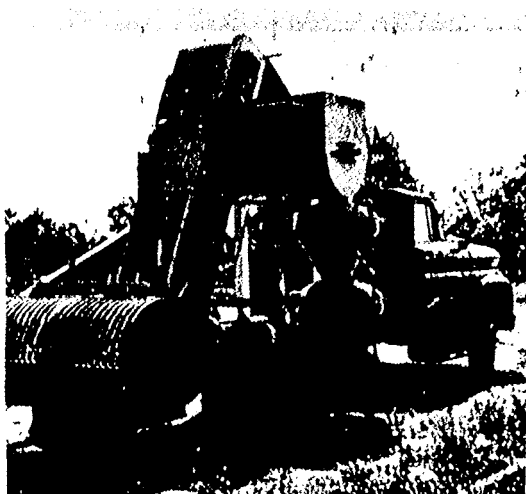


Fig. 2-2 Typical high-production shotcreting rig contains a mixer, an elevator, and a double-chamber gun. An adequate air compressor is required to complete the mobile outfit.

Optional equipment by another manufacturer includes with the screw elevator a heater for drying sand. The principal purpose of the heater is to provide a mix with optimum moisture content. Any job with wet sand, i.e., moisture content exceeding 5 to 6 percent, should have some provision for heating or drying sand. The main purpose of moisture control is to improve equipment operation, but other benefits such as somewhat improved accuracy of batching may result.

Such equipment would also be excellent for application of shotcrete in cold weather where a warm aggregate and water are desirable to reduce possibility of freezing.

Double-chamber gun

A typical double-chamber gun is shown in Fig. 2-3. With the lower cone valve closed, and the machine feeding the dry mix from the pressurized lower chamber to the material hose, the opened top chamber is recharged. The upper cone valve is then closed and the auxiliary air valve opened. When the pressure in the top chamber equals the pressure in the lower chamber (some 50 to 100 psi), the lower cone valve falls open and the mix drops by gravity into the lower chamber. In the lower chamber a feed wheel, agitator, or modified screw operated by auxiliary motor conducts the material into a flowing stream of compressed air directly entering the material hose.

The operation of a double-hopper gun is interesting. A good operator must be conscientiously trained to maintain his equipment and to operate it in such manner that a smooth flow of material reaches the nozzle at all times. In the startup, the gun is

normally at least half full and frequently full in both chambers. The upper valve or gate, which closes the entrance to the top hopper, is secured against a rubber gasket resembling an O-ring. The internal pressure sets the gate tight against the gasket and pressure becomes uniform throughout the two chambers. As the mix is fed into the material hose, the upper chamber is rapidly emptied. Between the two chambers is another gate or cone which is closed when the upper chamber is empty. The air pressure may then safely be exhausted from the upper chamber and the upper gate opened. New material is admitted to the upper chamber, the gate closed, and air pressure introduced. During recharging, material is still flowing from the partially full pressurized lower chamber. When air pressure is again balanced between upper and lower chambers, the lower gate is open and the fresh charge drops from upper to lower chamber. The cycle is repeated as long as placing shotcrete continues.

Single-chamber gun

One shotcreting rig with a single-chamber gun operates something like a pistol with revolving cylinder pointed straight at the ground. The barrel of the gun may be considered as the material

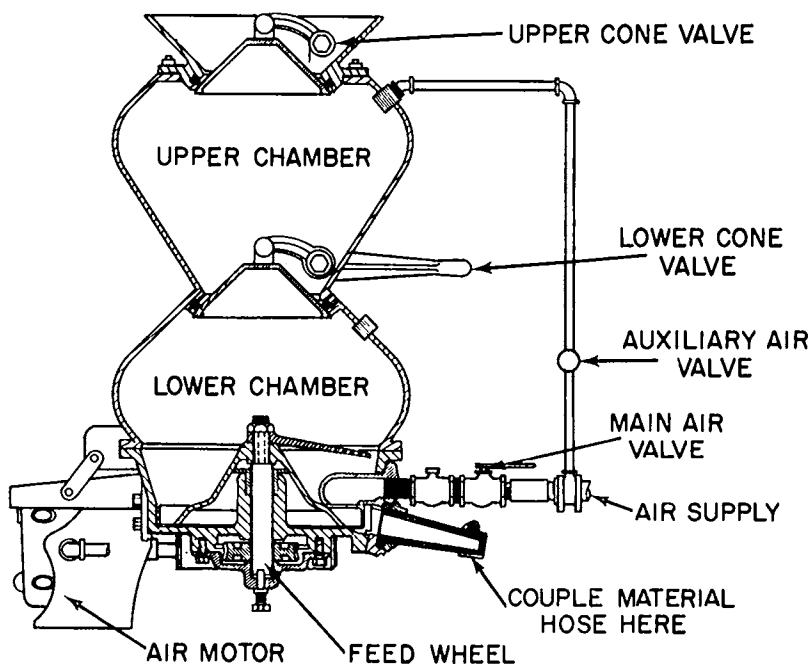


Fig. 2-3 Vertical section of typical double-chamber gun

hose and the revolving cylinder or rotor as the feeder to the hose. This machine has such a rotor of large diameter which turns in a horizontal plane. By an ingenious arrangement of gaskets, pressure is maintained in the air stream which passes from the bottom of the rotor at a point analogous to the gun barrel. At the opposite side of the circle the individual cells of the rotor are open at the top to the atmosphere. A hopper containing the mix is placed over this latter point. As the individual cells rotate under the hopper, they are filled with a charge which then revolves around and passes through the discharge air stream. The air stream picks up the charge of material and flows down through the material hose. The empty cell then rotates on to the hopper area for recharging. Nine of these cells comprise the rotor which turns rapidly introducing a fairly smooth stream of material into the distributor and hose. The high production version of this outfit has a rated capacity of up to 12 cu yd per hr.

MATERIALS

For dry-mix shotcrete, the normal procedure is to use Type I portland cement in paper bags. Bulk batching machines have been recently developed, but are not yet widely used. Type II and Type III cements are also frequently used to meet job requirements. High alumina cement is used for special work.

Any good concrete sand is suitable for shotcrete work. Normally a sand with a fineness modulus of around 2.5 is specified. In order to keep the gun and hose scoured out, the larger aggregate particles are most desirable. Where the coarse sand is unavailable, mortar sands will work just as well, but it is a little more difficult to keep the equipment clean. Where sponge-float and trowel finishes are required, the final coating of shotcrete could best be placed with a finer or mortar-type sand.

In addition to the normal aggregates, many specialty contractors shoot lightweight, refractory, and other special aggregates.

Admixtures can also be included in shotcrete. Normally, they are added through the mixing water. It is usually necessary to use a small tank of 500 or 1000-gal. capacity to which the admixtures are proportioned. The shooting water is then pumped from this tank. Some manufacturers produce admixtures with controlled solubility, which can be added from a container placed directly in the water hose line. Most such admixtures are for reducing surface tension of the water. It is claimed that the resulting improved wetting of the dry mix reduces rebound. Air entrainment has not yet been satisfactorily developed for dry-mix shotcrete applications.

APPLICATION OF SHOTCRETE

Supporting base

A good base or foundation is necessary for proper and successful shotcrete application. In the case of restoration of existing concrete, surfaces must be cleaned of all deteriorated materials, neutralized if any acids have been present, and absolutely cleaned. When shooting against formwork, the forms can be somewhat less stable than for concrete work. It is easy and surprising to demonstrate that shotcrete may be built up against the very softest type of insulation material without serious damage to or compaction of the soft material.

Proper placement

Good equipment alone does not make good shotcrete. The key to successful shotcrete application is a skilled crew working under proper supervision. With good equipment and crew, the following are necessary for proper placement of shotcrete:

1. Smooth flow of material
2. Sufficient water supply and pressure
3. Sufficient nozzle velocity
4. Proper positioning and mobility of the nozzleman.

The smooth flow of materials is achieved by having good equipment properly maintained and cleaned, correct hose and hose lengths, suitable mixes and moisture control of material, plus a well-trained gun operator.

Sufficient water supply and pressure can be secured by pumping and by proper water hose and coupling size. Often the mistake is made of securing the right size hose, but using couplings which constrict water flow to less than half of the hose size. A good, quick-acting water valve at the nozzle, a proper water ring with sufficient holes, and a good pressure permit the nozzleman to maintain proper water-cement ratio.

The nozzle velocity depends upon compressor size or capacity, hose sizes, nozzle tip opening, and clean equipment. The actual velocity of impingement also depends upon the distance the nozzle is held from the point of impact. The closer the nozzle is to point of impact, the higher will be the velocity.

The correct nozzle stream can be readily identified by an experienced nozzleman. Uniformity of color, velocity, and spray pattern are important. The angle of the nozzle in relation to the surface being shot is of key consideration. The amount of rebound, which depends on many of the above-mentioned factors, must also be given careful consideration.

Once the material is in place, it also has a characteristic appearance which tells the good shotcrete man the quality of the work being done. The surface will not be of a dry sandy texture, but rather should be the appearance of a rich, creamy icing on the cake. If the surface is excessively wet on a wall, it will show runs, drippings, cracks, or slides. On a floor, excessively wet shotcrete is soupy; puddles form and a man cannot walk across the newly shot surface, as he should be able to do, without sinking in. In shooting vertical or overhead surfaces, if the coating is too heavy or too wet large areas will drop out.

Sand pockets

Perhaps the greatest difficulty with shotcrete and the one which demands the most attention is the problem of sand pockets. Considerable attention should be given to surface cleaning and preparation before shotcreting commences. Yet, all of this preparatory work can be quickly wasted if the flying rebound is permitted to accumulate to even a small degree against the clean surfaces. Such rebound creates sand pockets.

A sand pocket is any inclusion lacking a rich cement paste which encases and is thoroughly mixed with all sand particles; such inclusions are porous, granular semivoids of low strength and poor bonding properties.

Sand pockets build up most quickly at inside corners, at the base of walls, behind obstructions such as reinforcing bars and pipes, or on horizontal surfaces. Slugs of the material—that is sudden bursts of material through the nozzle—can also create sand pockets through lack of proper hydration.

At the beginning of any shooting operation, the nozzleman should quickly fill all internal corners or potential sand pocket

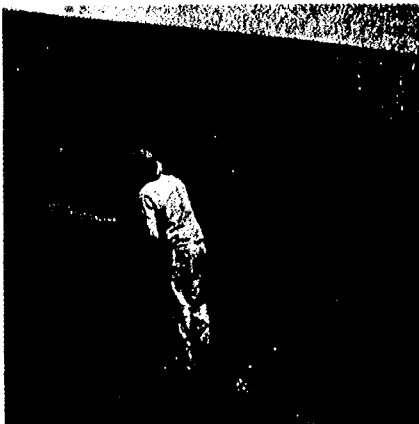


Fig. 2-4 On a vertical wall the nozzleman always shoots slightly upward and square to the wall. The nozzle is not pointed or swung in an angle from side to side, but moved square to wall.

areas. Usually a limited area or “unit” should be chosen for the work. The nozzleman should concentrate on this unit until it is fairly well filled out to finished lines. Then he will proceed to the next unit, from which all rebound and cement dust have been removed, again initially filling internal corners and potential sand pocket producers with sound shotcrete.

To reduce sand-pocketing, many contractors use a ¾-in. or 1-in. air blowpipe to remove accumulated rebound. In the construction of wire-prestressed composite tanks, the full air-water blast from the material hose is used not only to remove rebound, but to thoroughly clean all surfaces before encasement.

Nozzle techniques

The distance the nozzle is held from the point of application is very important. The optimum distance varies, depending on nozzle tip size, hose size, production, air compressor size, velocity of wind, skill of nozzleman, and type of surface being coated. On large, flat, unobstructed surfaces with 2-in. hose and a 600 cu ft per min or larger air compressor, the nozzle can safely be held back 6, 8, or 10 ft to produce perfectly satisfactory work. For example, many thousands of square feet of reservoir lining have been shot at high production rates with the nozzle at least 10 ft above point of application. In contrast, shotcrete has been applied inside of fume ducts 2 ft high and 4 ft wide. In this latter case, the quality of work suffered, but the end product was still superior to other available methods of corrosion protection.

For reinforcing bar or wire encasement, the nozzle should be held as close as practical. When shooting a finish flash coat over work which has been troweled, screeded, or otherwise worked, the further back the nozzle, the smoother and more attractive will be the finished surface.

The nozzleman is taught to hold the nozzle at 90 deg to the surface on which shotcrete is being applied (Fig. 2-4). Waving the nozzle continually changes the angle of impact, and each wave of the nozzle creates increased rebound, additional dust, and flying vapors. The only exception to shooting normal to the surface is when application is being made to an interior corner. Here the corner should be shot at approximately 45 deg to the intersecting planes. As the corner is filled and the nozzle moved up onto the vertical wall or out onto the horizontal floor, the angle of the nozzle becomes 90 deg again.

Frequently it is necessary to place shotcrete on a vertical wall adjacent to the ground. If the nozzleman holds his nozzle down almost flat to the ground and normal to the wall, a considerable



Fig. 2-5 Nozzle held low to shoot base of wall, but not so low as to pick up sand from ground. Hose-dragger leaves 3 or 4 ft of slack hose on ground immediately behind nozzleman for ease of handling by nozzleman.

amount of loose dirt will be picked up from the ground and entrapped with the shotcrete against the wall. This produces a very low quality shotcrete at the base of the wall. It is suggested that under these circumstances, as shooting approaches the base of the wall, the nozzleman does shoot at a small downward angle to reduce the possibility of rebound and dirt pickup from the floor or ground (see Fig. 2-5).

Material may occasionally come through the hose in slugs because of low air pressure, improper equipment operation, or wet sand. Under such circumstances, it is standard procedure for the nozzleman to direct the nozzle stream away from the place of application. Occasionally this can be dangerous to nearby personnel, who may receive the full force of the nozzle stream. Spraying of adjacent areas also increases cost of cleanup, as well as perhaps causing property damage.

For mild slugging, another solution is to move the nozzle back a reasonable distance and distribute the slugs over a large surface area. Often an unexpected slug will create a lump of unhydrated material on the surface. Under these circumstances the nozzleman should move a little aside in his shooting and permit the assistant nozzleman, hose-dragger, or finisher to cut out the bad material and permit the spot to be reshot.

Shotcrete is placed by compressed air, and only the cement, sand, and water remain in place. All of the compressed air used, plus the rebound, must escape from the point of impact. If the

compressed air and rebound cannot readily escape to the sides, then a turbulence is created at the point of impact which will seriously affect the end product in place. This means that it is quite difficult to place satisfactory shotcrete in a small diameter hole of any depth or in deep slots or other places of confinement. A perfect example of poor technique would be the shotcreting of a standard 6x12-in. waxed cardboard cylinder for test purposes. This is not at all recommended.

ENCASEMENT OF REINFORCEMENT

Because of the danger of sand pocket inclusion behind reinforcing bars, size of bar is a consideration. It is recommended that under normal circumstances a #5 bar be the maximum size used. It is almost certain that bars of larger size will produce "shadowing" or sand pockets. A skilled nozzleman can normally quite satisfactorily encase #5 or smaller bars with good shotcrete.

Frequently the steel detailers will specify #2 bars as ties or spacers. Wherever possible, such practice is to be avoided. Each unnecessary bar is an opportunity for careless workmanship and subsequent sand pockets.

A sand pocket behind a reinforcing bar is particularly serious in a thin wall as it can be a considerable portion of the full cross section at the bar. The reduced area occasioned by the sand pocket will permit a stress concentration in the cross section. Very frequently a crack develops parallel to the bar, through the sand pocket (see Fig. 2-6). In hydraulic structures water sometimes gets into a network of sand pockets behind the bars, penetrating throughout the entire structure.

To prevent sand pockets behind reinforcing bars, the nozzle should be held close enough to the bar to force the material around and behind the bar while keeping the front side of the bar substantially clean and free from material buildup until the entire bar is encased. If the nozzle is held back from the reinforcing bar a sufficient distance to permit the material to fluff up to and accumulate on the front side of the bar like wet snow, then severe sand pocketing will occur on the back side. Many recommend that a reinforcing bar be shot from two sides or two directions. Even though this may be relatively simple to do, if material is permitted to build up on the bar from either or both directions, a sand pocket will develop behind the bar. Where proper procedures are followed, excellent encasement of the reinforcement is obtained (Fig. 2-7).

Where circumstances permit, it is the writer's personal preference to place reinforcing steel directly against either the formwork



Fig. 2-6 Extreme flaw resulting from bad shotcreting practice and improperly spliced bars. Two #4 bars were tied at the lap splice. The nozzle was about 4 ft from the bars, and material was permitted to build up on the front face of bars before the back was fully encased. The weakened section cracked through during sawing.

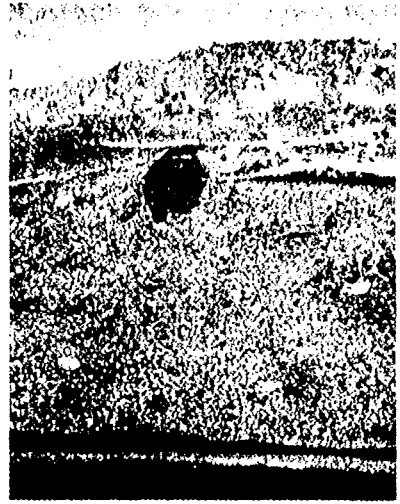


Fig. 2-7 Perfect encasement of a #4 bar, with nozzle held about 2 ft away and directed from several angles during shooting. The material hose was 100 ft long and 1½ inches in diameter. A 365 cu ft per min air compressor was used. Uniform shotcrete completely surrounds and protects the bar.

or existing shotcrete or concrete surfaces. The intimate contact of the bar with its backing assures that even the poorest nozzleman cannot shoot a very large sand pocket behind the bar. A good nozzleman will shoot the same bar with no sand pocket. When the bar is placed directly against the formwork, the reinforcing bar and initial shotcrete are coated from the back side after form removal.

When gunning a floor, the reinforcing mesh should be pulled up off the dirt or form so that it is embedded as nearly as possible at the center of the slab (Fig. 2-8).

Quite often a design calls for two curtains of reinforcement. If convenient for work schedules, only the first curtain of reinforcement should be placed at the outset, in such manner that it is encased with the first layer of shotcrete placed. The steel should be embedded in the first layer to reduce possibility of shrinkage cracking. After the first steel is encased, the second layer of reinforcement may be set and encased. If a nozzleman endeavors to shoot through two curtains of reinforcement, considerable rebound may occur and the danger of sand pockets increases tremendously.

Fig. 2-8 Shooting a tank floor. Reinforcement is pulled up so that it will be as close as possible to the center of the slab.



In conventional concrete construction, the laps of reinforcing steel are tied together. Minimum laps are specified by code to take into account reduced bond area created by tying the bars together. In shotcrete, it is extremely difficult to properly encase such a lap. In fact, the lapped bars tied together will usually create a rather large sand pocket behind the bars (see Fig. 2-9). Consequently it is recommended for shotcrete construction that lapped bars be spaced at least two diameters apart, and preferably even more. This will simplify the nozzleman's work and improve the quality of the finished job.

Bundling of prestressing wires, which may occur around pipe or wall openings, can also cause sand pockets and voids (Fig. 2-10). Proper specifications should rule out such bundling in shotcreted structures, and require that the prestressing wires lie in a flat plane

Fig. 2-9 Improperly lapped reinforcement. Knobs of shotcrete which had built up on the front face have been broken off to permit photographing. Note holes behind bars.





Fig. 2-10 Sand pockets and voids develop where prestressing wires are bundled. Such bundles of wire may occur around pipe or wall openings.

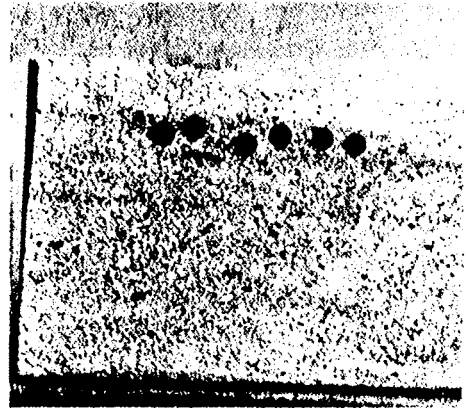


Fig. 2-11 Complete encasement of No. 8 prestressing wire achieved by keeping wires in a flat plane and giving careful attention to shotcreting techniques

(as in Fig. 2-11) at a minimum spacing of about one wire diameter. The first layer of shotcrete over the wire should be a 1:3 mix, shot slightly wetter than normal and just thick enough to barely encase the wire. This first thin layer should not be screeded or finished except for a light brooming. When more than one layer of wire is to be used, the bottom layers should be encased at least to the depth of each wire before additional wires are placed.

PRODUCTION RATE

High production is often a most desirable accomplishment of the shotcrete contractor. In swimming pool work it is not uncommon for a good contractor to shotcrete an entire small pool in the morning and another entire pool that same afternoon. To do this, large, highly portable equipment is required. Often an air compressor is mounted on a truck and some type of trailer-mounted unit towed behind. The material is delivered to the job site in advance. When the shotcrete outfit arrives on job site, the nozzle and hose are unreeled and shooting commences almost immediately. After completion of the shotcrete, the hose is reeled back up and the equipment is off to the next job.

Shooting rates of 25 to 60 bags of cement in 1:4 to 1:5 mix per hour are possible with good equipment. Depending on whether the material is being placed on a horizontal surface shooting downward, a vertical surface, or overhead, and depending also on the type of

finish required, the material in place (or yield) amounts to between about 20 and 33 board feet per bag of cement in 1:4 mix. High production rates do not necessarily affect the quality of the work when proper attention is given to details.

BOND

Frequently the engineer is concerned with the type of construction joint to be used with shotcrete. A long tapered joint is generally standard. A shotcrete joint, where new shotcrete is applied to an existing clean surface of older shotcrete or concrete, can be close to 100 percent efficient. Many cores have been cut from walls consisting of multiple layers of shotcrete. Where the workmanship is anywhere near suitable, the layers are indistinguishable one from another except perhaps for varying shades or color. When such cylinders are tested, they give the normal characteristic break of a homogeneous isotropic material.

Test samples of shotcrete have been bonded to other shotcrete, concrete, brick, and stone. Attempts to separate the layers usually result in a break not along the boundary plane but extending deep into one or the other material.

When shooting is discontinued for the night, there is no concern about cold joints, only clean joints. When shotcreting is resumed the next day, the bonding surfaces are given a hard air-water blast for good cleaning and then shooting resumes. The nozzleman carefully prewets with shotcrete all of the surface to be bonded. He moves rapidly along the joint, assuring that a good, light bonding coat of shotcrete is applied before any rebound or cement dust can accumulate against the freshly cleaned surface. The wet new bonding coat can accept a small amount of dust and sand without problem, but should be refreshed frequently.

The high efficiency of bond is true whether there be a one-hour or one-decade lapse between applications. The important thing is that the surface be cleaned before shotcreting commences, and that an initial layer of good shotcrete be placed against the bonding surfaces before rebound can collect on the clean surface.

CURING

Early and good curing of shotcrete is perhaps more important than for concrete. Usually concrete is placed in much heavier layers than shotcrete. It takes a longer time for the thicker concrete layers, perhaps formed on two sides, to dry out than it does for the thin shotcrete layers. During the first few days after shotcrete

placement, the surface is quite receptive to moisture and seems to have a high absorption capacity. As the chemical reactions occur, the surface becomes more and more impervious to water until eventually good shotcrete becomes virtually waterproof.

The purpose of curing is twofold: It permits the chemical hydration which is so important to strength gain. At the same time, it delays and reduces initial shrinkage with its accompanying cracking. After a suitable period of curing, say 7 to 10 days, depending on conditions, the shotcrete will have attained such tensile strength that the possibility of shrinkage cracking or crazing is considerably reduced.

SURFACE FINISH

Often shotcrete work is rough and perhaps anything but attractive. However, true straight lines and fine surface textures are readily attainable in shotcrete. As a matter of fact, the skilled contractor can normally obtain better lines and better finishes with shotcrete than is possible with concrete. When placing concrete, it is almost inevitable that some small amount of form bulging and distortion occurs. Certainly all form marks cannot be concealed. In shotcrete work, proper rodding will eliminate all undesirable bulging, leaving true surfaces (Fig. 2-12). Should corners be ragged, hollows be formed, or any surface damage occur, it can be readily repaired by subsequent shotcrete application. After all rodding is completed for truing of lines, a light, final flash coat will give an attractive dappled or sandy texture to the surface.



Fig. 2-12 Screeding to shooting wires with wood screed cut to finished surface radius. Shotcrete is stiff enough to resist having cracks dragged into the surface.

WEATHER

Poor shotcrete can be caused by unfavorable weather conditions when placement occurs outdoors. Excessive winds tend to segregate cement and sand. Cement in the form of fine droplets of wet paste can be distributed for several hundred yards downwind from point of application. The main jet stream from the nozzle can be partially segregated also, permitting both overly rich and cement-poor areas to develop.

Rain can cause heavy visible damage by washing the fresh shotcrete completely away or badly streaking it. A more insidious type of destruction can be the penetration of moisture into the fresh shotcrete with little or no apparent damage. However, beneath the surface, internal cracking and separation can occur, particularly in the area of reinforcement. On partially set shotcrete, rain may also wash off some of the surface, leaving very coarse aggregate and cement-poor material. All damage of this type to surfaces should be thoroughly cleaned and reshot.

Hot weather shotcreting is less critical than is hot weather placement of conventional concrete. In placing concrete, the problems that develop are because of handling, finishing, and cold joints. Where shotcrete is actually hydrated at the nozzle and sprayed into its final position in the matter of a second, these troubles are less significant, particularly if little or no finishing is required. If finishing is required, enough men must be available to keep ahead of the danger of final set. Early and adequate curing must be provided, however.

Cold weather shotcreting presents serious problems. Freezing of the fresh mix can be destructive. Frost on the surface can prevent bond of subsequent layers. Before shotcreting under freezing conditions, protective measures should be taken.

QUALITY CONTROL

The ACI Standard 506-66, "Recommended Practice for Shotcrete," * describes testing and nozzleman qualification procedures. Good quality-control testing is also essential to a proper shotcrete job. The methods of preparing shotcrete test specimens are still open to much discussion among the authorities.

One of several methods is to shoot a 4 in. diameter, 5 in. high cylinder in ½-in. wire cloth. Shortly after shooting, the 5-in. cylinder is trimmed to the outside of the hardware cloth and permitted

* Reprinted in full on p. 193.

to set. After it is thoroughly cured the prescribed time, the hardware cloth is removed, and the specimen tested. Normally, a correction is made for the length-to-diameter ratio. This type of cylinder gives reliable, reasonably consistent results and is indicative of the strength of the material being applied.

Another method used for qualifying nozzlemen as well as obtaining test specimens is to shoot test panels 2 or 3 ft square, and 2 in. or more thick, using typical reinforcement for the job. Compressive strength tests are made on 6x12-in. or 6x6-in. cylinders or cubes of various sizes sawed from these panels. When the test panel is cored, cut up, or broken open, it will be indicative not only of the strength, but of the skill of the nozzleman, suitability of the mix, and the effectiveness of the reinforcement.

The only true way to determine the quality of the shotcrete in place is to core the structure. Such coring should by all means include some of the reinforcing bars, so that they can be inspected for adequate encasement.

RECOMMENDATIONS

There are few, if any, more durable or better construction materials than good shotcrete. Most complaints about shotcrete can be traced to poor workmanship, improper training of operators, or a lack of understanding of the uses and capacity of the processes.

To assure good shotcrete, there must be constant training, continuous testing, and conscientious, knowledgeable inspection. With all these factors present, shotcrete will give excellent service as a versatile and effective construction material.

PAPER NO. 3 Experience with dry-mix coarse-aggregate shotcrete, applied in layers up to about 6 in. thick, has proved it structurally adequate for both temporary and permanent underground support. Recommended ingredients, mix proportioning, and application techniques are explained, and mixing and placing devices are described in some detail.

Recommendations for testing and quality control procedures are outlined. How coarse-aggregate shotcrete meets requirements for various types of tunnel work is shown with details of its use on specific projects. Cost is compared with that of conventional tunnel support media.

Dry-Mix Coarse-Aggregate Shotcrete as Underground Support

By **HELMUT G. KOBLER**

■ **SHOTCRETING WITH MORTAR MIXES** has been successfully performed for the past 50 years on many varied types of surface and underground construction throughout the world. However, the use of such mixes permits application only in relatively thin layers. Also, when air-placed mortar has been used exclusively as support of underground excavations it has not always exhibited the qualities desired of a competent supporting material, and its uses underground have therefore frequently been restricted to semistructural applications.

There was obviously a need for new equipment and operation procedures which allow the modern engineer to spray structurally sound concrete in thick layers. During the past 20 years substantial progress in this direction has been made. Several types of delivery equipment, fully capable of spraying structurally sound concrete containing coarse aggregates larger than 1 in., are now available. This equipment, together with advances in the proportioning of

concrete mixes and the development of chemical admixtures, has made possible the successful application of dry-mix coarse-aggregate shotcrete in layers more than 6 in. thick.

Initial equipment development and its subsequent successful use for thin-shell roof construction, tunnel and shaft lining, and for lateral support of open-cut excavations were confined largely to construction sites in Europe and South America. Therefore, few engineers in North America are acquainted with these developments. It is the purpose of this paper to report on experience gained from the application of dry-mix coarse-aggregate shotcrete, particularly its use for temporary and permanent underground support.

FUNDAMENTALS OF DRY-MIX COARSE-AGGREGATE SHOTCRETING

Principles of application of dry-mix coarse-aggregate shotcrete are basically the same as for the gunning of mortar by the dry-mix process. However, specially designed delivery equipment, together with the use of special chemical admixtures, permits the spraying of structurally sound coarse aggregate concrete in much thicker layers of application than was possible with the original dry-mix fine-aggregate process.

The ingredients for coarse-aggregate shotcrete—consisting of standard or special types of cement, sand, and coarse aggregates graded up to 1¼ in.—are mixed dry and fed into the aggregate hopper of the delivery equipment. The mix is then mechanically fed into a pressure chamber, from which it is blown by a strong, high-velocity air stream through a flexible hose to the discharge nozzle. Water is introduced and manually regulated at the nozzle, hydrating the dry mix (suspended in the air stream) to the required consistency. The amount of water added is controlled at all

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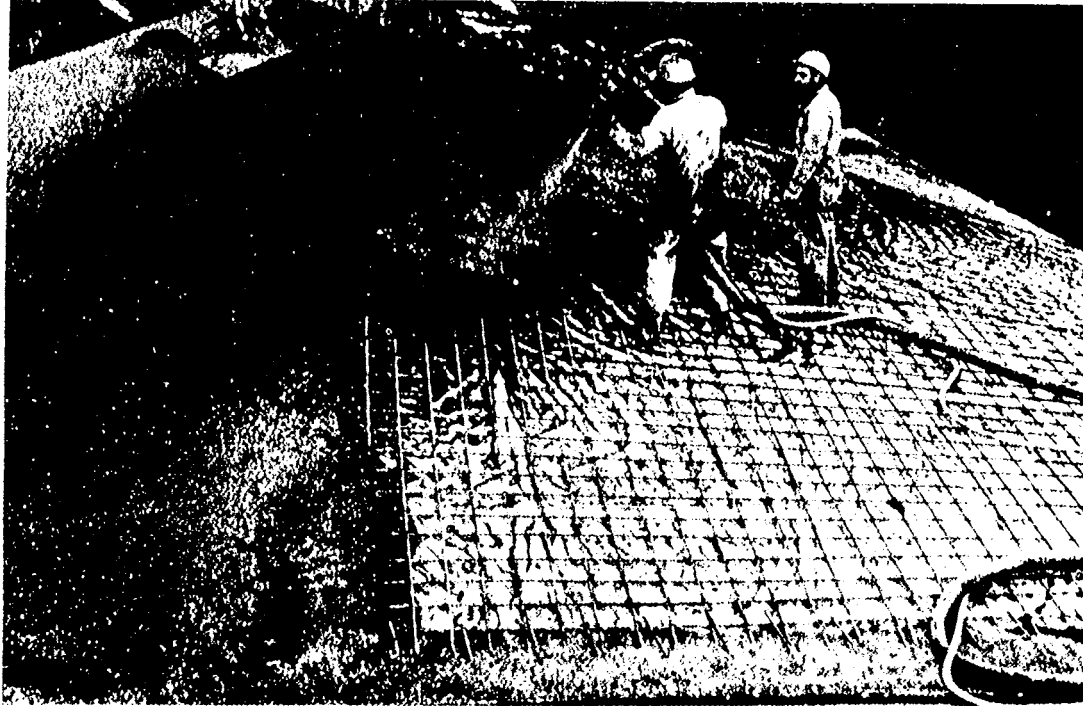


Fig. 3-1 Dry-mix coarse-aggregate shotcrete has been used for surface construction as well as underground. Here workmen are gunning the roof of a service station in Vancouver (1961).

times by the nozzleman, who is responsible for the continuity of proper application and hydration.

The author has found that coarse-aggregate shotcrete applied by this method is stronger and denser, and has a lower slump and water-cement ratio than is generally found in conventionally placed concrete. The inclusion of coarse aggregate in the mix reduces cement content and shrinkage. Dry-mixed coarse-aggregate shotcrete bonds well to other materials and has excellent waterproofing qualities. These properties are attained in the field and have been substantiated in numerous laboratory tests. In Europe and South America, dry-mixed coarse-aggregate shotcrete has become a well established, economical construction material. It has been used to a lesser extent in North America. Applications include surface construction (see Fig. 3-1) as well as underground structures.

As in the case of conventionally placed concrete, the successful use of coarse-aggregate shotcrete depends on many contributing factors, and well established guidelines must be followed as closely as possible to obtain a satisfactory final product. Of utmost importance are proper hydration,* size and gradation of aggregates, water-cement ratio, provision for rebound, and proper application procedures.

* See definition in glossary, p. 192.

Aggregate

Fine and coarse aggregates used in this process should conform to current ASTM specifications, and should be reasonably dry and clean. The use of fine aggregates ($0\text{--}\frac{1}{4}$ in.), containing more than 2 percent of microscopic dust (below 0.2 mm) should be avoided, since the dust tends to form a harmful coating of the particles, adversely affecting the cementing process. The fineness modulus should be in the range from 2.4 to 3.2.

Although coarse aggregates up to $1\frac{1}{4}$ -in. maximum can be used, it is recommended that the maximum size be limited to 1 in. Experience has shown that rebound increases and delivery equipment efficiency decreases when aggregates larger than 1 in. are used.

Coarse aggregates should be properly graded, chemically stable, and have adequate compressive strength. Although natural, well rounded aggregates are preferred, crushed rock aggregates are satisfactory and give essentially the same strength for mixes of equal cement content. However, aggregates having rough textures or a high percentage of flat and elongated pieces should be avoided, since their presence in the mix may adversely affect the water-cement ratio. In general, aggregates that do not exhibit a large deficiency or excess of any one size, and which have a smooth

TABLE 3-1 COMMONLY USED AGGREGATE GRADINGS FOR FINE- AND COARSE-AGGREGATE SHOTCRETE

Amounts finer than each size, percent by weight										
Aggregate size, mm		0.2	1	3	7	10	15	20	25	30
Aggregate size, in.		1/64	3/64	1/8	9/32	25/64	19/32	25/32	63/64	1 3/16
FINE-AGGREGATE SHOTCRETE	Conventionally used	2-15	20-40	50-75	100					
	A.M.B.*	2-15	20-40	56-72	100					
	Drögsler †	8-22	30-50	64-80	100					
	Drögsler Average ††	15	40	72	100					
	Line B (see Fig. 3-2)	15	40	72	100					
	ASTM	5-17	41-75	78-92	97-100	100				
COARSE-AGGREGATE SHOTCRETE	Conventionally used	2-15	20-40	50-75	90-95	100				
	Conventionally used	5-20	20-40	30-65	50-80	—	100			
	Conventionally used	5-20	20-40	30-65	50-80	—	80-95	100		
	Conventionally used	5-20	20-40	30-50	50-70	—	70-90	—	100	
	Drögsler †	5-15	18-34	36-50	55-73	—	80-94	—	—	100
	Drögsler Average ††	10	26	40	64	—	87	—	—	100
	Line E (Fig. 3-2)	9	24	43	60	—	82	—	—	100

* "Anweisung für Mörtel und Beton," Deutsche Bundesbahn DV 806-1949 (German railroad standards).

† See Reference 1.

†† Based on mean values for the Drögsler grading ranges shown.

grading curve, will produce satisfactory results (see Table 3-1). Gap-graded aggregates, especially in the coarser grade range, have sometimes produced higher strength shotcrete than conventionally graded aggregates.

Nearly ideal results are obtained when aggregates are introduced into the mixer in five separate size groups. These groups should be as follows:

Fine aggregate (sand) from 0 to $\frac{1}{4}$ in.—50 to 60 percent

Group No. 1: From 0 to $\frac{1}{8}$ in. (not more than 2 percent of dust (finer than $\frac{1}{64}$ in.))

Group No. 2: From $\frac{1}{8}$ to $\frac{1}{4}$ in.

Coarse aggregate from $\frac{1}{4}$ to 1 in. (or $1\frac{1}{4}$ in.)—40 to 50 percent

Group No. 3: From $\frac{1}{4}$ to $\frac{1}{2}$ in.

Group No. 4: From $\frac{1}{2}$ to $\frac{3}{4}$ in.

Group No. 5: From $\frac{3}{4}$ to 1 in. (or $1\frac{1}{4}$ in.)

While this ideal grouping of aggregate is not always practical in the field, it should be considered where superior quality shotcrete is desired.

As a rule, aggregates conforming to the grading band superimposed on Line E of the grading chart proposed by Rothfuchs * (Fig. 3-2) will give satisfactory results. The grading shown in Fig. 3-3, which is recommended by one equipment manufacturer, is also satisfactory. Care in selection of suitable aggregate content and grading cannot be overemphasized, since a poor selection cannot be later corrected by intensive vibration, as in the case of conventionally placed concrete.

Proportioning coarse-aggregate shotcrete

As for conventional concrete, the quality of coarse-aggregate shotcrete depends to a considerable extent on the proportioning of the mix. For economy, one should use the minimum cement content possible without sacrifice of quality. Since quality depends primarily on the water-cement ratio, water must be kept to a minimum in order to reduce cement requirements. Using coarse aggregates of maximum permissible size in the shotcrete mix holds the water-cement ratio to a bare minimum without adversely affecting the maximum attainable strength of the concrete.

In the dry-mix coarse-aggregate process, water-cement ratio is the easiest factor to control, and ranges from 0.32 to 0.40, depending on the size, gradation, and quality of aggregate used. For mixes

* An Austrian authority on concrete and aggregate, cited by Drögsler in Reference 1.

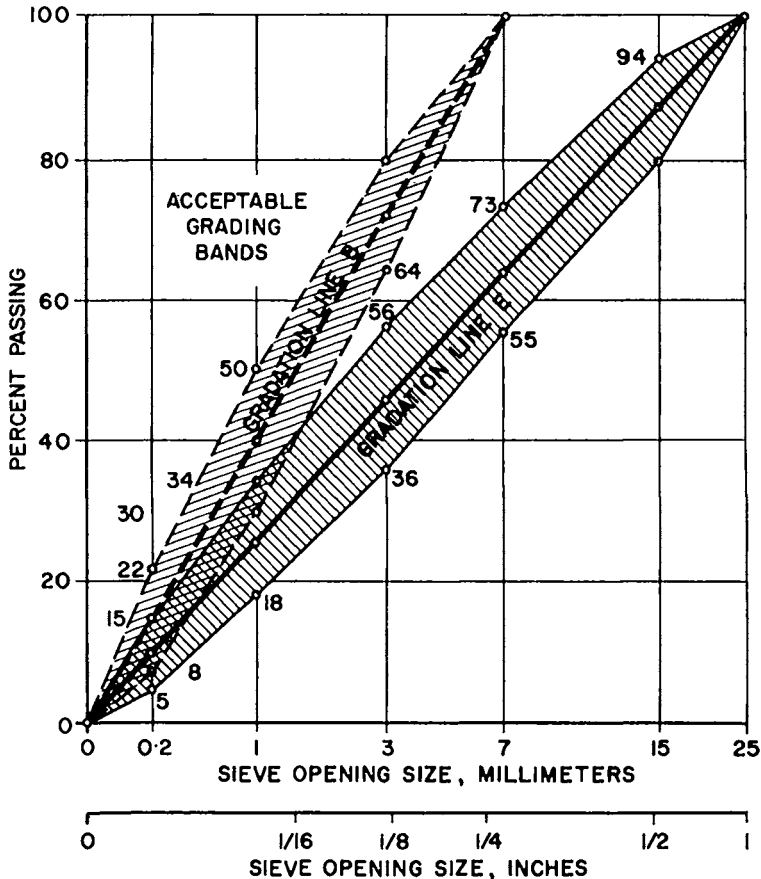


Fig. 3-2 Aggregate grading for shotcrete recommended by Rothfuchs.¹ Gradation Line B for shotcrete with fine aggregate up to $\frac{1}{4}$ in.; Line E for shotcrete with coarse aggregate up to 1 in.

containing aggregates larger than 1 in. a water-cement ratio of 0.34 to 0.37 is ideal, and can be easily obtained (see Fig. 3-4). Cement content may range from 500 lb per cu yd for shotcrete of 4500- to 5000-psi strength using maximum size aggregate (in excess of 1 in.), to 650 lb per cu yd for shotcrete of 5500- to 6000-psi strength for mixes with aggregates up to $\frac{1}{2}$ in. Certain admixtures may increase compressive strength into the 7000-psi range; however, such strength is rarely required and should only be considered for special application purposes.

As compared with conventional concrete, a somewhat higher tensile strength is desired of shotcrete, especially when it is used for underground support. As a rule, *ultimate* tensile and compres-

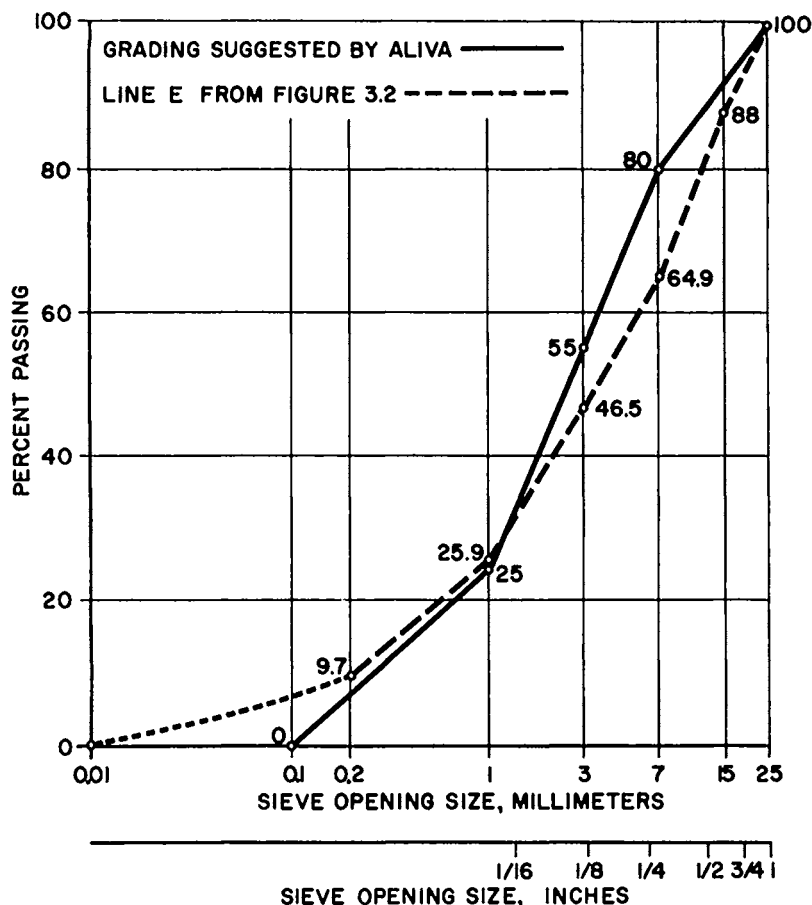


Fig. 3-3 Aggregate grading for coarse-aggregate shotcrete suggested for use with Aliva BS-12, compared with Line E of Fig. 3-2

sive strength in underground applications are of secondary consideration, since the maximum stresses in the support zone occur early in the setting process. In extreme cases this is only a few hours after completion of the excavation and subsequent shotcrete application. Therefore, the principal aim in the proportioning of coarse-aggregate shotcrete for underground support should be an economical mix that will develop maximum strength at an early age.

Type I portland cement should be used whenever possible. Where shotcrete is exposed to severe sulfate attack, portland blast furnace and pozzolan cements may be used. High alumina cements are rarely used.

Admixtures

A number of special chemical admixtures which increase early strengths, decrease rebound, and increase freezing resistance are available for specific job conditions. It is advisable, however, to carefully contemplate their advantages, influences, and limitations before using them. Only well tested and proven admixtures should be considered; remember that some admixtures which are beneficial in regular concrete may not be quite as useful in coarse-aggregate shotcrete.

Either dry or liquid admixtures can be used. However, for the dry-mix coarse-aggregate process, the author prefers admixtures in powder form since liquid admixtures tend to complicate the mixing procedures. Calcium chloride or similar accelerating chemicals added to the dry mix in powdered form, in an amount of 2 to 6 percent of the cement weight, will accelerate the initial set to such an extent that compressive strengths of 200 to 250 psi will be

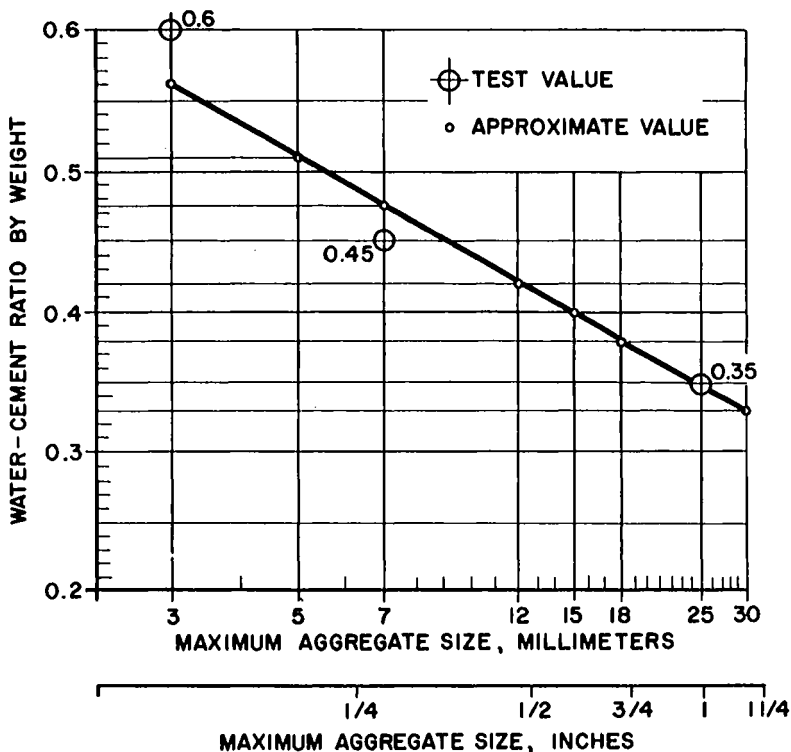


Fig. 3-4 Effect of aggregate size on water-cement ratio for shotcretes of equal cement content (aggregate grading corresponding to Lines B and E of Fig. 3-2)

obtained during the first 2 hr, 800 psi in 12 hr, and up to 1500 psi in 24 hr. When used for the purpose of reducing rebound, 2 to 3 percent of this additive is sufficient.

Hydration

Hydration (addition of mixing water) and water-cement ratio are continuously controlled by the nozzleman. Hydration deficiencies can readily be observed and instantly corrected. Underhydration produces dust and excessive rebound. Sagging and sloughing of the applied mix indicate overhydration and can be at once eliminated.

Hydration is a function of nozzle flow and water pressure. Fluctuation of water pressure will adversely affect proper hydration and should not be tolerated. Water line pressure should be constant and should not fall below 70 psi. Whenever possible, it is recommended that the water pressure be maintained a few pounds above the air pressure in the discharge hose. To eliminate unfavorable fluctuation of water pressure, an air-driven piston-type water pump drawing water from an open-top reservoir should be used. The quality of water required is the same as for conventional concrete.

Operations conducted in high-humidity areas, especially in underground work, are usually accompanied by unfavorable condensation conditions in the lines supplying compressed air to the delivery equipment. Excessive condensation water in the discharge hose will result in prehydration of the passing mix, causing the line to clog. This can be largely overcome by placing a small air receiver equipped with a drain valve in the air line. Such an air receiver, located near the delivery equipment, will not only collect and drain the condensation water but will be most useful in maintaining a reasonably constant pressure of air supplied to the delivery unit.

Rebound

In the application of coarse-aggregate shotcrete, rebound becomes a most important consideration, and for economy should be kept to a minimum. The amount of rebound depends on many factors such as hydration efficiency, water-cement ratio, fine and coarse aggregate content, aggregate gradation, nozzle velocity, nozzle flow, angle and distance of impact, application thickness, and the application skill of the nozzleman.

The quantity of rebound for properly proportioned and correctly applied coarse-aggregate shotcrete ranges from 5 to 15 percent for vertical walls, increasing to 20 and 25 percent for overhead work (see Fig. 3-5). In shotcrete applied for underground support, the average amount of rebound is between 20 and 25 percent. During

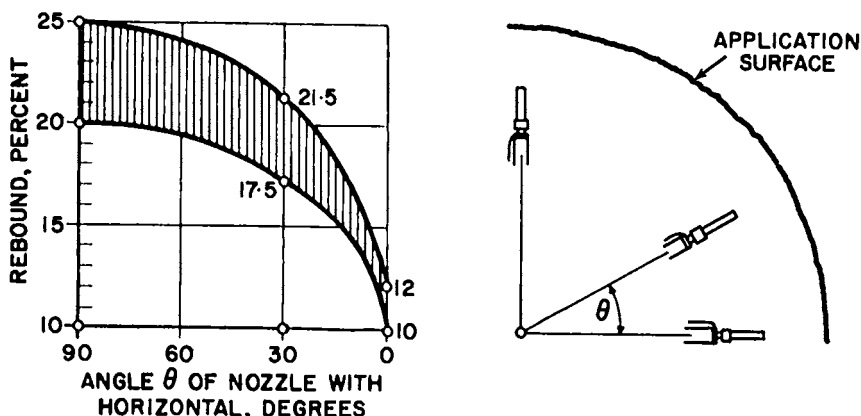


Fig. 3-5 Effect of gunning direction on percentage of rebound. Note that nozzle is kept at right angles to application surface, while the angle it makes with the horizontal varies.

the initial stages, the percentage of rebound is always excessive, but it soon diminishes after a plastic cement-sand cushion has been formed on the application surface, permitting the coarser aggregates to become embedded in the matrix.

The percent of rebound is also affected by the distance of the nozzle from the application surface as indicated in Fig. 3-6. The amount of rebound can generally be held to an acceptable minimum if the distance between nozzle and application surface is about 3 to 3½ ft and the nozzle is kept as nearly perpendicular to the application surface as possible. Addition of 2 to 3 percent of a suitable chemical accelerator to the mix will greatly assist in minimizing the amount of rebound.

Gradation of rebound is usually much coarser than the original mix itself, since only the larger particles tend to ricochet. Numerous examinations and tests indicate that the cement content of the

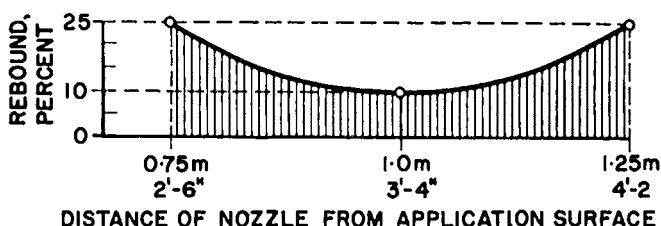


Fig. 3-6 Percent of rebound as affected by distance of nozzle from application surface

rebound ranges between 10 and 40 percent of the cement content of the shotcrete mix. It is felt that 10 to 15 percent can be considered as average.

The reuse of rebound is not recommended. Should this practice be contemplated, the material should be thoroughly washed prior to reintroduction into the delivery equipment. Tests of shotcrete in place, where rebound was used, have indicated a decrease in strength between 20 and 30 percent. Considering the labor involved in collecting rebound and its adverse influence on the quality of the shotcrete in place, the economic advantages are negligible indeed.

Because of the variability in the amount of rebound, it is somewhat difficult to determine the volume of dry mix required for a given volume of shotcrete in place. Experience seems to indicate that 1.3 to 1.7 cu yd of dry mix is required to produce 1 cu yd of coarse-aggregate shotcrete in place. For underground work, where much of the application is overhead, an average of 1.6 to 1.7 cu yd has been attained on several jobs.

Surface preparation, application, and curing

Shotcrete will adhere to almost any surface, even if it is as smooth as polished steel. However, for the most satisfactory bonding, some surface treatment is essential. This is particularly true when coarse-aggregate shotcrete is used. The application surface must be clean and free of any loose or foreign material. This may be achieved by first directing a strong, water-saturated compressed air stream onto the surface; later, sand is added to the air-water stream and the area is in effect sandblasted as desired.

Once the surface has thus been cleaned and treated, the shotcrete application is begun by spraying a thin, rich, cement-sand grout base coat. Such a base coat creates a suitable bedding cushion for the application of the coarser mix, and should be kept at a low water-cement ratio whenever water seepage conditions occur. As soon as this base layer has been placed, the remainder of the application may proceed by spraying a steady concrete stream in a circular fashion. Layers 2 to 3 in. thick are progressively built up until the desired application thickness is achieved.

Thicknesses exceeding 8 in. have been satisfactorily achieved for a single application; nevertheless, it is generally advisable to restrict each operation to a thickness of 6 in. Should a shotcrete thickness exceeding 6 in. be desired, there should be a 6- to 12-hr wait (depending on mix proportions), in order to avoid any disturbance to the initial setting process. As a rule, 500-psi compressive strength is needed for the shotcrete in place before making a further application. There is no limit on the number of successive

applications, provided undue interference with the initial setting period of the previous application is avoided.

To obtain the best quality and durability from coarse-aggregate shotcrete, proper curing is essential. Because of rebound, coarse-aggregate shotcrete contains more cement than conventional concrete of the same proportions, and adequate curing is needed to prevent the formation of cracks. However, shotcrete applied for underground support purposes rarely requires special curing, since humidity in the atmosphere of underground workings is usually sufficient to effect a satisfactory curing process.

Quick-setting chemical admixtures, together with the low water-cement ratio characteristic of dry-mix coarse-aggregate shotcrete, facilitate operations during subzero temperatures. The use of admixtures to provide resistance to freezing should be most carefully considered and, whenever possible, completely avoided. Their presence in the mix may adversely affect the ultimate strength of the shotcrete in place. Generally, suitable anti-freezing precautions may be achieved by other means such as preheating of aggregates, raising the temperature of the mixing water, the use of space heaters, and other well established field procedures.

EQUIPMENT FOR COARSE-AGGREGATE SHOTCRETING

Mixing equipment

Depending on job conditions and job requirements, the ingredients for dry-mixed coarse-aggregate shotcrete may be mixed by manual labor, by conventional mechanical mixer, or by transit-mix truck. Standard methods governing a correct mixing operation should be followed and special precautions must be taken to avoid prehydration of the dry mix. Standard practice for underground operation is to place a small mechanical mixer before the delivery equipment, discharging the dry mix onto a small loading platform or into a small storage hopper. The mix is then fed at the required rate by two workers or a small conveyor belt into the delivery equipment. Provided suitable space is available, the cement and aggregates required to maintain a continuous operation may be stored underground near the delivery plant.

For work in close quarters, such as small-diameter tunnels, it is necessary to transport the dry-mixed material in batches to the delivery equipment. In such cases, large delays between the mixing process and the application must be avoided and the dry mix should be continuously examined for evidence of prehydration. Special conditions may make it necessary to premix the fine and

coarse aggregates at the surface, transport them in suitable batches underground, and add cement at the delivery equipment.

Delivery equipment

To the author's knowledge, there are three leading types of concrete spraying equipment using the dry-mix principle (Fig. 3-7). The Torkret S 3/II and the BSM 603, 604, and 606 are manufactured in Germany and are basically of the same double-pressure-vessel design. Material is fed in batches to both of these units. The Aliva BS-12, manufactured in Switzerland, has an open aggregate holder which permits continuous uninterrupted feeding. All three models are capable of spraying coarse-aggregate shotcrete of satisfactory quality and thickness, but the Aliva machine has the greatest capacity.

In the United States the Air Placement Equipment Company recently reported a successful test of dry-mix coarse-aggregate shotcrete on a railroad tunnel in Nevada. Shotcrete applied by their equipment using a modified feed wheel included coarse aggregate graded up to $\frac{3}{4}$ in. Tests of a number of specimens indicated an average compressive strength of 3680 psi at 7 days, and 4480 psi at 28 days. Additional information as to thickness of application, water-cement ratio, aggregate gradation, and other contributing factors would be required to evaluate results in detail.

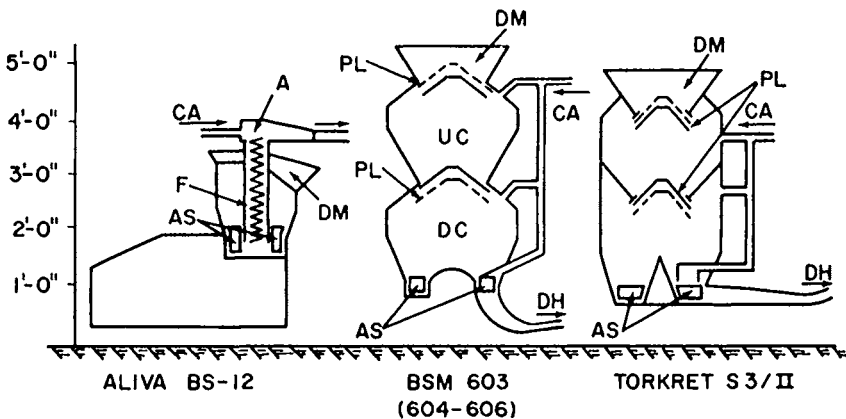


Fig. 3-7 Components of dry-mix coarse-aggregate shotcrete delivery equipment

DM—dry mix point of entry
AS—agitation system
F—screw-type feeder
CA—compressed air intake
A—blow chamber

DH—discharge hose and discharge nozzle
PL—pressure locks
IL—interchamber locks
DC—discharge chamber
UC—upper chamber

The Aliva BS-12 machine—This unit, invented in 1942 by the Swiss engineer Georg Seen, is the only operational single-open-chamber machine capable of spraying coarse-aggregate shotcrete. At first, only aggregates of ½-in. size could be used, but the equipment was subsequently modified by the Swiss manufacturer to handle coarse aggregates up to 1¼ in., and has been marketed for the past 10 years as the Aliva BS-12 concrete spraying machine. The bulk of experience gained by the writer in the use of dry-mix coarse-aggregate shotcrete was in connection with the use of this machine on a number of surface and underground operations.

This unit eliminates the adverse characteristics of the pressure-chamber-type spraying equipment by incorporating an open dry-mix hopper with a vertically mounted, circular screw-type feeder in the center. At the extreme upper end of the screw-type feeder is a small horizontal bell-type pressure chamber. Compressed air is introduced into the chamber at one end, blowing the dry mix into a discharge hose and on to a specially equipped discharge nozzle. Hydration takes place inside the nozzle, where a perforated O-ring introduces the required mixing water under pressure to the passing dry mix.

Power to operate the feed mechanism is supplied by an air, gasoline, or electric motor located on the chassis alongside the hopper.

Mounted on rubber tires, the unit is mobile and compact—only 4.5 ft high, 5.0 ft long, 2.5 ft wide—and weighs 1750 lb. Compressed air consumption is about 280 cu ft per min at 80 to 100 psi. Power requirement for electrical operation is 20 hp. Output capacity of the Aliva BS-12 is from 5 to 9 cu yd of dry mix per hr. A conservative average of 5 cu yd per hr for underground work has been established.

By interchanging a few parts, this unit can be converted to a concrete placing machine, pumping low-slump concrete containing 1½-in. aggregate at the rate of 10 cu yd per hr through a 4-in. flexible discharge hose. On tunnel construction projects, it has become common to use the BS-12 as a spraying machine for temporary support and later to use two units in tandem for placing concrete in the permanent lining.

QUALITY CONTROL AND TESTING PROCEDURES

To ascertain the quality of coarse-aggregate shotcrete in place, it is of utmost importance to establish and closely follow a quality-control system based on sound and realistic testing procedures.

Conventional concrete is placed at a predetermined water-cement ratio and vibrated to obtain compaction; in contrast, dry-mix coarse-aggregate shotcrete is air-transported and intensively vibrated by impact. Its hydration is manually controlled and the water-cement ratio can be altered at will. Deficiencies in application procedures will increase the amount of rebound, and the rebound will influence the quality of the material in place. Whenever coarse-aggregate shotcrete is to be tested, these factors must be taken into account, and fabrication of specimens for compressive and tensile tests should reflect, and duplicate in every possible aspect, conditions prevailing during application. Test results obtained should be carefully scrutinized and well documented.

It is most incorrect (but frequently done) to prepare a test mix of proportioned ingredients, to mix and hydrate it to a required consistency, and then place the material in conventional testing cylinders. Specimens prepared in this manner do not exhibit the slightest resemblance to the quality of the shotcrete in place. Test results obtained from such specimens are most unrealistic and completely useless for the purpose of quality control.

The practice of jetting a test mix into specially prepared specimen boxes or standard test cylinders is also not recommended, since rebound material may be retained in the specimen and material segregation may occur in the corners of the molds. Past experience in the preparation of samples for compressive and tensile strength tests of dry-mix coarse-aggregate shotcrete indicates that the most satisfactory specimen is obtained when a specially built three-sided wood form, about 3x3 ft, is attached to the application surface in such position that the open bottom part of the form will allow rebound to fall free. The test mix is then shot onto the form in the conventional manner, to the required application thickness. Soon after application while the material inside the form is still plastic, thin metal strips are gently forced between the fresh concrete and the box at a desired spacing to interrupt bond and facilitate later removal. Samples are then pried from the form at the required age, and suitable test cubes are cut and tested.

The simplest and most reliable, but somewhat more expensive, method of obtaining test specimens is to core-drill standard-sized cylinder specimens from the shotcrete in the structure at the desired ages. A number of inexpensive, hand-held diamond core drills are available for this purpose. Samples for compressive and tensile strength should be cored both parallel and perpendicular to the bedding laminations. It is at times convenient to include in the test mix a suitable coloring agent, in order to delineate each individual application coat. Usually such lamination zones can be easily dis-

tinguished, since almost invariably a finer textured material precedes each coarse aggregate application coat.

Whenever less accurate results will suffice, an impact hammer or other conventional mechanical test may be satisfactory, provided it is conducted properly and systematically. Durability and frost-effect tests are conducted in the same manner as for conventional concrete.

Cracking

On some occasions, particularly where sand-rich shotcrete mixes are used, the shotcrete in place may exhibit shrinkage cracks. Where shotcrete is used for underground support purposes, such cracks may cause concern by giving the impression of some form of quality defect or structural damage. To ascertain whether such fractures are due to initial shrinkage effects or to serious structural deficiencies, a small channel—approximately 6 to 8 in. long and 2 to 4 in. wide—is chipped out from the lining on either side of the crack and then filled with plaster of paris. These areas should be periodically examined. Should no new cracks appear in the plaster, it can be assumed that no structural weaknesses are present and the original cracks can generally be attributed to initial shrinkage effects.

UNDERGROUND SUPPORT REQUIREMENTS

Besides meeting safety considerations for the crew working at the face, underground support should be designed to rigidly support and prevent loosening of the surrounding rock formation. It should also hermetically seal as closely as possible the exposed rock surface and attain maximum carrying capacity as early as possible after installation. Principal materials used for underground support are timber, steel, and concrete. Of these, timber is least satisfactory because of its tendency to yield. Structural steel arches, which are in many respects superior to timber, are not perfectly satisfactory since their efficiency as a support depends on wood blocking and on the quality of packing between the support arch and rock above. Manual or mechanical packing by nature is rarely fully effective, and its capacity to resist and transmit developing rock loads is doubtful.

Concrete in general and properly applied coarse-aggregate shotcrete in particular fully meet the requirements for competent underground support. Because it offers high early compressive and tensile strength, maximum density, impermeability, and good

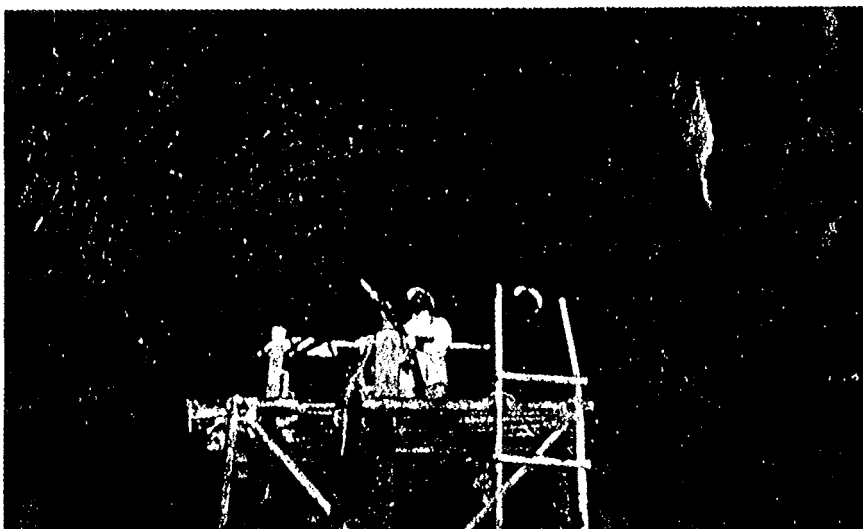


Fig. 3-8 Shotcrete 6 in. thick, applied in two layers, was used as permanent lining for subway tunnel in Toronto in 1961.

bond, pneumatically applied concrete has found widespread use in underground construction and mine operations.

As early as 1911 George Rice, chief engineer of the Pittsburgh Bureau of Mines, recognized some of these qualities in pneumatically applied mortar. He is credited with the first practical underground application of fine-grained shotcrete in 1914, at the Brucetown Experimental Mine. Thereafter, pneumatically applied mortar was used as underground support, although mainly in semi-structural applications.

The recent development of dry-mix coarse-aggregate shotcrete created renewed interest in the process, and its successful use during the past 15 years on a great number of underground projects has proved its suitability as an economical and structurally competent temporary and permanent underground support (Fig. 3-8).

Design considerations

Success and efficiency of a shotcrete support depend a great deal on correct evaluation of geological conditions and prevailing structural deficiencies of the surrounding rock formation. Physical and chemical action of the rocks must be carefully studied and provided for in the structural design. High early strength, adequate load-carrying capacity, and an intimate interaction of the shotcrete with surrounding rock are significant factors in the design.

Proper consideration of these features makes it possible to safely use working stresses close to the ultimate strength of the material, particularly if the shotcrete lining is intended to serve only as a temporary support. If the shotcrete eventually attains a permanent character, or becomes a structural component of the permanent support, a safety factor from 1.5 to 2 should be used.

When designing a shotcrete lining, standard practices for underground supporting structures should be followed. The favorable interaction of shotcrete with the surrounding rocks is rarely considered in the design, but it permits the designer to adopt minimum values of forces when estimating contributing active forces in calculations of lining thickness.

At first, this may appear a somewhat daring statement to make. However, it is substantiated by numerous competent field studies, together with many miles of successfully executed tunnel construction.

Temporary support requirements

One of the principal aims in tunnel and lateral underground excavation is the maximum advance per excavation cycle with a minimum time expenditure. Excavation methods and related maximum lengths of cycle advance depend primarily on the capabilities of the excavated area to remain static and self-supporting from the time initial excavation commences until partial or complete disintegration of the surrounding rocks occurs.

Depending on geological conditions and petrographic aspects of the formation in question, this nearly static period may extend anywhere from a few hours to a few days, governing accordingly the choice of proper excavation procedures, length of cycle advance, and type and quality of the temporary support required. Depending on cross section of the excavation and the type of support used, the time required to effect suitable temporary support may range from 25 to 80 percent of the total excavation cycle time. Support operations are, almost without exception, time consuming and nonproductive; therefore, the support medium must be carefully selected to save time, labor, and material costs.

Suitability of temporary support depends on a number of special requirements and considerations. Especially important is the capability to establish without delay complete, intimate contact between the support medium and the material requiring stabilization.

Once installed, temporary support should require little or no additional maintenance. Whenever possible, support operations should be carried out concurrently with other steps of the excavation cycle. Structurally, temporary support must sustain initial rock