Technical Report **R 429**

ENGINEERING PROPERTIES OF SHOTCRETE

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Technical Report R-429

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by

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ABSTRACT

The important technical information gleaned from a literature survey covering the past 55 years of laboratory and field experiences with mortars and concretes applied pneumatically (i.e., shotcrete) is presented. In addition to general facts concerning this method of construction, various physical properties of hardened shotcrete, which have been investigated by numerous researchers, are discussed. Insofar as strength and elasticity are concerned, hardened shotcrete generally is quite similar to hardened mortar or concrete made in the conventional manner and fully compacted. An experimental program is recommended for (1) developing supplementary data with regard to density, elasticity, and strength (bond, compressive, and flexural) of hardened shotcretes (premixed wet) made with 3/4-inch as well as 3/8-inch maximum-size aggregate, and (2) ascertaining whether or not comparatively small prismatic test specimens truly represent the engineering properties of hardened shotcrete in large wall panels.

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INTRODUCTION

Purpose of Investigation

The objective of this task is to develop data concerning the physical properties of structural mortars or concretes that have been placed pneumatically. The end product desired is a report presenting engineering data for use in designing and specifying pneumatically placed mortars or concretes for Navy structures ashore. The U. S. Naval Civil Engineering Laboratory (NCEL) has used pneumatically placed mortars or concretes for constructing prototypes of personnel shelters. A comparatively brief search for information, prior to the erection of such prototype shelters, was made by Webb (1961) and indicated a scarcity of data on the engineering properties of this type of mortar or concrete. Accordingly, the Bureau of Yards and Docks (BuDocks) requested the Laboratory to make a literature search to determine the extent of information available on the physical properties of pneumatically placed mortars or concretes. The following are considered important physical properties: unit weight (bulk density); voids; strength (bond, compressive, flexural, shear, tensile); Young's modulus; shrinkage and swellage; creep; contraction and expansion; moisture absorption; permeability; and durability (resistance to abrasion, fire, and alternate freezing and thawing).

Answers to the following questions are desired: (1) Is a satisfactory bond achieved between successive layers of pneumatically applied mortar or concrete? (2) Is the compressive strength of pneumatically placed mortar or concrete equal to that of conventional concrete? (3) Will thinner shells of reinforced concrete applied pneumatically in the form of personnel shelters and ammunition magazines be as strong as thicker, conventionally placed shells? (4) Is thin-shell, pneumatically applied concrete or mortar construction adaptable to Navy structures such as warehouses and barracks?

Definition of Shotcrete and Rebound

Pneumatically placed mortar or concrete is also known as shotcrete. This term is not proprietary, is accepted by the American Concrete Institute (ACI), and may be known by different names in different geographical areas. The term was first adopted by the American Railway Engineering Association (AREA) about 1930, Hirschthal (1937).

Shotcrete may be defined as follows:

> Mortar or concrete that has been conveyed (by regulated air pressure or by positive-displacement pump or screw) through a hose and discharged through a nozzle (usually hand-held) at high velocity onto a suitably prepared inflexible surface; the product, which has been premixed either dry (water added at the nozzle) or wet (water added prior to entry into the hose), is sufficiently stiff at impaction to support itself without sagging from an overhead surface or sloughing from a vertical surface.

Basically, fine shotcrete is mortar, and coarse shotcrete is concrete. In the literature, fine shotcrete is most often designated Gunite, although it is also known as sprayed mortar, pressure-applied mortar, or pneumatically applied mortar. Shotcrete is also referred to by proprietary terms, e. g., Blastcrete, Blocrete, Bondact, Guncrete, Gunite, Jetcrete, Nucrete, Pneukret, Spraycrete, and Torkret; Gunite is undoubtedly the best-known term.

Concrete pneumatically conveyed via steel pipeline to the forms, but not ejected at high velocity, is customarily known as pneumatic concrete. When it is forced through the pipeline by a special type of pump, it is customarily called pumped concrete (in proprietary terminology, Pumpcrete).

Rebound may be defined as follows:

> A mixture of spent shotcrete material, leaner and coarser than the original mixture, that has bounced off the surface during impaction; expressed as percent of the original mixture.

The U. S. Bureau of Reclamation (USBR) has found that rebound becomes excessive when the aggregate is larger than 0.375 inch.

Previous Shotcrete Investigations at NCEL

The Laboratory's use of shotcrete has been limited to prototypes of ammunition magazines and personnel shelters. The first investigation of shotcrete at NCEL was described by Wiehle (1953a and 1953b). Eight years later Webb (1961) investigated techniques for forming premixed-wet shotcrete as a constructional method in connection with the development of a full-scale prototype personnel shelter intended to serve as an alternate to existent BuDocks standard shelters. His experiment disclosed that the use of shotcrete containing 0.500-inch maximum aggregate was feasible and economical. Allgood et al (1962) subsequently recommended design criteria for underground shelters constructed of shotcrete.

GENERAL FACTS ABOUT SHOTCRETE CONSTRUCTION

The general information in this section is intended to give sufficient background to those unfamiliar with shotcrete construction so they can better understand its engineering properties, which are discussed in the next section.

Shotcrete is used in the construction of new concrete structures and for repairing, restoring, strengthening, or waterproofing existent concrete or masonry structures; it is employed as protective coating for steel structural members, masonry, and foundation rock; and it is useful also in placing relatively shallow linings, as in some tunnel work and in canals. Shotcrete can be gunned against any appropriate sturdy surface, including earth, to a thickness of several inches without sloughing or sagging.

The principle of the cement gun was discovered in 1907 by Carl E. Akeley (sculptor, naturalist, explorer) of the American Museum of Natural History. The device he invented was a result of his experiments incident to building mounts for trophies. The carcasses were formed by spraying plaster of paris onto an expanded-metal frame of the required shape. He soon concluded that this apparatus was better suited for applying mortar. Within 3 years, the device had been improved by the Cement Gun Company, Allentown, Pennsylvania. In 1910 the patented device was designated Cement Gun by Byron C. Collier, president of that firm (now Allentown Pneumatic Gun Company).

The term Gunite was coined by Collier in 1911 to describe the mortar product applied by the Cement Gun. The term Gunite first appeared in the engineering literature about 1914; Guncrete, in 1925; Pneucrete, in 1929; and Blocrete, in 1953. Gunite, Jetcrete, Cement-Gun, and other similar expressions, are proprietary; their use is appropriate only when the proprietary method or equipment is involved. These terms, as well as shotcrete, denote concrete or mortar pneumatically gunned or shot into place through a nozzle; the terms should not be confused with pneumatic concrete, which is simply pneumatically conveyed through pipes into forms.

The attributes of shotcrete were first outlined by Prentiss (1911) as follows: (1) inexpensive operation, (2) operational continuity, (3) operational flexibility, (4) homogeneous concrete in place, and (5) greater density than that of conventionally placed concrete. Shotcrete has undergone many improvements since its introduction as a constructional method. Better equipment and new developments in application technique now permit rapid construction and insure the rehabilitation of deteriorated structures. Ease of application and minimum formwork add to shotcrete's usefulness. The method is usable at any location which can be reached by a hose. The earliest comprehensive paper on the subject of the Cement Gun and Gunite was that by Weber (1914).

The first structural engineering application of the Cement Gun occurred when the old Marshall Field Museum of Natural History in Chicago, Illinois, was covered with a coat of gypsum stucco. As early as 1914, Gunite had been used at

Hawaii, in the Panama Canal, at Puerto Rico, in the Croton Aqueduct in New York State, in California reservoirs (San Francisco, Los Angeles, and San Diego areas), and in a Spanish viaduct. According to Collier (1922), in 1912 the Los Angeles Cement Gun Company constructed a Gunite reservoir in Pasadena, California. This structure was 80 feet in diameter; the dome had a rise of 13 feet, and the walls of the dome were 1.5 inches thick at the top and 2 inches thick at the shoulders.

One of the earliest large-scale applications of Gunite was in the construction of the underground terminal yards of Grand Central Station, New York, New York, where an area of 5,000,000 square feet was covered before completion of the job in 1918. The Southern California Edison Company has used Gunite since 1917 for repairing various hydro-electric structures. Likewise, the East Bay Municipal Utility District, Oakland, California, has made extensive use of this constructional material. Gunite construction in mines was first undertaken during 1915 at the U. S. Bureau of Mines experimental mine, near Pittsburgh, Pennsylvania, where the walls of the passageways were lined; subsequent experiments were conducted to ascertain the fireproofing characteristics of Gunite applied to timber struts. The earliest application of Gunite in Central America occurred in 1925 when it was used for lining a 1,000,000-gallon reservoir at San Juancito, Honduras. In 1962 the Gunite Contractors Association at Los Angeles estimated that the annual production of shotcrete in the United States was over 1,000,000 cubic yards.

According to Young (1937), shotcrete fulfills its intended purpose reasonably well despite its cracks and occasional lack of bond. Regardless, the Soviets apparently do not have confidence in shotcrete as a means of repairing deteriorated concrete structures. According to Sedov (1958), shotcrete is unsatisfactory for enhancing the durability of structural concrete because the bond of the shotcrete to the underlying concrete is unreliable, even when special metallic fabric is used.

Shotcrete construction is considered economical, compared to conventional cast-in-place concrete construction, because formwork is simpler and less restricted in tolerances. For example, since 1920 the Eastman Kodak Company plant at Rochester, New York, has realized considerable savings by constructing tanks of shotcrete instead of wood (Fairchild, 1935). A shotcrete structure usually has fewer joints, and may or may not have less steel reinforcement, than conventional concrete. The shotcrete constructional methods described by Webb (1959) show that cementitious mixtures incorporating coarse aggregate, maximum size 0.750 inch, can be successfully sprayed by pneumatic jet.

According to Kidder and Parker (1952), "Tests have shown that Gunite is superior in tensile and compressive strength, and adhesion, with less permeability, absorption, and porosity than good hand-made or deposited concretes or cement mortars...As a result of a series of tests conducted at the Underwriters Laboratories (Robinson et al, 1922), the following time - temperature ratings were secured on various walls and partitions of Gunite: hollow 12-inch walls on Gunite studs, 3-hour; solid 2-inch non-bearing Gunite partitions, 1-hour."

According to Troxell and Davis (1956), "The advantages of pneumatically placed mortar are ease of placement with minimum need for forms and plant, high strength, and good durability when exposed to freezing and thawing. Its disadvantages include high shrinkage, a wide range in quality dependent upon the skill of the nozzleman, relatively high porosity and permeability, and a different moisture shrinkage and coefficient of expansion than for the old concrete in the structure. For many kinds of repair the advantages of this method are considered to outweigh the disadvantages (see Chadwick, 1947 ACI Proceedings, 43:533). It has seen extensive application in the past, but many of the jobs have not given perfect service."

The advantages and disadvantages of shotcrete are covered in more detail in ACI Standard 805-51, and in the ensuing discussion thereof (Chadwick et al, 1951). According to Linder (1963), the production of shotcrete is subject to greater sources of error than any other modern type of concrete.

In applying shotcrete, the deposit is gradually increased, as incremental layers, until the desired total thickness is obtained. For practical reasons, the maximum thickness is usually 8 inches and the minimum is 1 inch. It is of interest to note that in 1926 the shotcrete lining of a tunnel at the Oakdale and South San Joaguin Irrigation District (Calif.) varied in thickness from 18 to 30 inches.

Two shotcrete methods are possible. In the "wet-mix" process, recognized officially by ACI Committee 805 (now 506) in 1962, the constituents (cement, aggregate, and water) are thoroughly mixed in either a conventional mixer or a pressurized tank, and the mixture is then forced through the delivery hose and nozzle. The equipment known as True Gun-All utilizes this system. In the "dry-mix" process, the cement and aggregate (both dry) are mixed in a suitable mixing device, then transferred into a feed chamber which, upon being pressurized, feeds the dry mixture through a hose into one inlet of a two-inlet nozzle. A second hose, furnishing water under pressure, is connected to the other inlet of the two-inlet nozzle. The water and dry mixture are combined and ejected in a moist condition; the nozzle operator controls the water content of the shotcrete in accordance with his judgment of suitable consistency. The wet-mix process obviously assures more uniform control of the water - cement ratio (W/C) than does the dry-mix process.

Formwork is simplified when using shotcrete. For example, only a supporting form (backing) surface and suitable steel-fabric reinforcement are needed to accommodate the deposition of mortar or concrete when erecting a wall; but the surface must be clean to assure proper bond. Steel reinforcement is installed not closer than 1 inch from the surface. The steel reinforcement required with shotcrete must be compatible with either flat or curved surfaces, and usually is relatively small-mesh (2 by 2 inches) welded-wire fabric that is prefabricated of high-tensile-strength steel. It can be installed speedily and is available either as plain or deformed reinforcement. Steel-fabric reinforcement finer than No. 12 wire is not rigid enough. Expanded metal is not as desirable, because sand pockets tend to form in the acute angles and create potentially weak spots. If the original steel reinforcement (in a structure being repaired) is corroded, the steel fabric must also serve as a replacement, in which event a heavier gage wire will be necessary.

In the case of restoring, repairing, or strengthening an existent concrete or masonry structure, the previous structural surface must be free of all extraneous material such as coatings or scale. A sandblasted or otherwise roughened structural surface, which must be structurally sound, serves as an adequate backing. The original concrete or masonry surface should be prepared carefully; pneumatic chipping hammers or manual tools are acceptable for preparing the surface, but if they are used indiscriminately they could damage an otherwise sound matrix beneath the roughened surface and consequently impair the potential bond of the shotcrete to the old concrete or masonry.

Whatever the form surface, it must be rigid enough to absorb the impact of the impinging shotcrete without undue vibration. The formwork configuration should be such that the air blast will be readily dissipated, and the rebound will be free to drop away while the shotcrete is deposited. Where shotcrete is applied to wooden surfaces, the wood should first be covered with either waterproof paper or form oil before the steel-fabric reinforcement is installed; otherwise, the wood tends to absorb moisture from the fresh shotcrete. Considerable dust arises during gunning operations and should be blown off the bare surface (including reinforcement) because it would prevent proper bonding.

If the deposition of any layer of shotcrete is interrupted, the layer should be tapered off to a feathered edge; otherwise, the resultant joint will create an objectionable pattern in the finished surface. When shotcreting is resumed, the bond of the succeeding deposition will be as satisfactory as if no interruption had occurred.

Shotcrete, as a protective coating over concrete, masonry, or steel, carries little load beyond its own weight. Nevertheless, such shotcrete is subject to tensile stresses induced by shrinkage, which is usual after the hardening process is underway. The tensile stresses cause shear stresses in the bond plane. Thus, shotcrete that exhibits the least shrinkage is likely to be the most durable. In those instances where the shotcrete serves as the structural member, rather than an encasing medium, shrinkage is still a vital factor. To prevent shrinkage of shotcrete, many contractors use an admixture of powdered iron in the amount of 15 pounds per bag of cement. While the shotcrete is hardening, the iron rusts, undergoing enough volume expansion to offset the natural shrinkage of the shotcrete. Without such an admixture, there is always the possibility that shrinkage may crack the shotcrete.

The cement used in shotcrete may be portland or aluminous. The high shrinkage rate associated with aluminous cement may weaken the bond between the shotcrete and the underlying structural material (in the case of restoration or encasement) unless the freshly gunned shotcrete is liberally sprayed with water. The repair of waterfront concrete structures with shotcrete containing sulfate-resistant (Type V) or high-early-strength (Type III) portland cement may be satisfactory if the initial set occurs before the repaired area is covered by the rising tide. The use of normal or standard (Type I) portland cement is quite general in routine shotcrete operations.

During placement of the initial coat of shotcrete on a hard surface (concrete, masonry, steel, glass, or wood) a film of cement paste bonds to the surface, and nearly all aggregate is lost by rebound. Only the extremely fine particles of sand and cement in the shotcrete mixture cling to the bare surface to create an evenly distributed matrix. During this initial spraying, the coarser particles are not cemented together and are lost as rebound. During the second and third coats, the amount of rebound decreases because the gradually thickening deposit is sufficiently plastic to permit the coarser particles to find a surface to cling to. The paste layer serves as a cushion as it gradually becomes thicker and begins to absorb the cement-coated aggregate particles in the subsequent blasts of shotcrete. When a particle strikes the matrix of cement paste, the particle embeds itself and adheres. When a particle, not covered with paste, strikes a partially embedded particle, the former rebounds and is lost; the blow, however, serves to drive the partially embedded particle deeper and more solidly into the mass, thus causing greater compaction. As the deposited mass grows thicker, each oncoming aggregate particle serves as a miniature tamper in compacting the freshly mixed shotcrete. Entrapped air bubbles cannot develop under such conditions. Rebound varies with the pressure, the distance of the nozzle from the surface being coated, the fineness of aggregate, the consistency of the mixture, and the shape of the structural member. The rebound contains very little cement. During initial deposition, as much as 95% of the aggregate in the original mixture may rebound; during subsequent gunning, the rebound is reduced and may consist of 20 to 50% of the original mixture. Sometimes a lime admixture is used to reduce rebound.

The W/C of shotcrete before deposition normally ranges between 3 and 5 gallons per bag. The best mixture should have a consistency so that if it were manually squeezed into the shape of a ball, only a trace of water would appear as a surface film; such consistency is equivalent to a slump between zero and 1 inch.

A mistake often made in premixed-dry fine shotcrete work is using sand that is too dry. Best results are obtained when the sand has 5% moisture (less than this amount causes dust at the nozzle), because then the shotcrete mixture will not segregate even in a long hose. Operating a shotcrete gun without dried compressed air may result in numerous shutdowns due to clogging of the gun or hose, or both; this is especially important during rainy weather. For premixed-dry fine shotcrete, the fine aggregate should contain 5% moisture to also preclude static electricity discharge (which interferes with proper handling of the nozzle) at the dry-mix inlet to the nozzle. The hose feeding the gun will most likely clog if the sand is too moist.

Mix proportions now are usually on a weight basis. The cement-aggregate ratio (C/A) usually ranges between 1:3 and 1:5 before placement. If the proportions of the mixture leaving the nozzle are 1:3.5, the proportions of the deposited mixture are quite likely to be about 1:2.5 due to rebound loss of aggregate. The actual proportions of the deposition will depend on the orientation of the surface being shot (horizontal, sloping, or vertical). The maximum-size aggregate in current practice is 0.500 inch. Though the nominal C/A of shotcrete is normally 1:4, it may vary from 1:2.5 to 1:5 depending on job circumstances and structural requirements. If the C/A before gunning is 1:3 by weight, the resultant reduction of the ratio in the deposited mixture will be about 1:2. Such a rich mixture develops more shrinkage stress than does a lean one and subsequently tends to produce hair cracks. Conversely, the leaner the mixture, the greater the rebound. Hence, there are practical limits for the C/A, and these must be met if shotcrete is to be worthwhile. Careful selection of the sand is essential because experience shows that the quality and gradation of sand are important factors in the durability of shotcrete. The type of sand used affects the working of the gun; very fine sand causes the gun to clog, whereas coarser grains keep the equipment passages scoured clean.

In the dry-mix process, the air pressure feeding the mixture of cement and aggregate to the nozzle inlet ranges from 35 to 70 psi, depending on the size of the nozzle outlet. The water pressure at the other inlet of the nozzle should be at least 10 psi greater and usually is about 20 psi greater than the air pressure. The hose length usually ranges from 50 to 150 feet, depending on the operating pressures. The nozzle is held 3 to 5 feet from the work and is pointed perpendicular to the surface to be covered. Air requirements are large, approximating 500 cfm for coarse shotcrete.

The shotcrete layers are from 1 to 3 inches thick, depending on consistency, specifications, or operator's judgment. The final layer is covered with a finish coat which may vary in thickness from 0.125 to 0.250 inch. The prime coat may vary from 0.50 to 4 inches, but a 2-inch layer is about the thickest that can be applied successfully in one sweep of the gun. One cubic yard of shotcrete mixture will result in at least 0.5 cubic yard of shotcrete in place.

Some authorities claim that the maximum practical thickness of each layer is 2 inches on a horizontal surface and about 1 inch on a vertical surface. Horizontal slabs may be built up to any thickness, but removal of rebound (if the shotcrete is gunned downwards vertically) could pose a serious problem.

Other authorities claim that the maximum thickness of fresh shotcrete applied in one layer in a vertical plane cannot exceed 3 inches, beyond which the freshly applied mixture begins to slough. When shotcrete is applied overhead, the limiting thickness is 1.5 inches, beyond which it begins to sag.

The surface appearance of hardened shotcrete is characteristically wavy, and the degree of waviness decreases as the skill of the nozzleman increases. Unlike conventional concrete, shotcrete sets quickly; thus, any use of wooden floats must be completed within 30 minutes after deposition. Tamping or steel-troweling deposited shotcrete is contrary to good practice, as its durability and bond strength may be adversely affected. To insure good bond between successive layers, a 1-hour delay between layers is the maximum period feasible.

For maximum density, the shotcrete should exhibit a faintly glossy appearance at the moment of application; the skill of the operators in achieving this is an important factor in shotcrete construction. Maximum density and minimum shrinkage cracking are compatible with high pressure impact and low W/C. If too much water is used, the constituents wash away; if too little water is used, the mixture cannot adhere. If the moisture content of the sand is not proper and the mixture is relatively rich, moisture variation in the sand can produce troublesome changes in the consistency of the shotcrete.

Since the force of the jet compacts the mortar or concrete in place, shotcrete placement requires a lower W/C than is customary with conventional construction. The density thus obtained and the stiffness of the mixture permit building up many shapes without conventional formwork. The following are examples: (1) thin walls; (2) coatings over concrete, masonry, and steel; (3) encasement of structural steel for fireproofing; and (4) repair of reinforced concrete structures.

The main advantage of shotcrete is the relatively small portable plant that is employed. To be economically justifiable, however, shotcrete must be placed by highly qualified workers, because strength, durability, and surface texture of the product are influenced by the operational techniques used.

According to Barron (1958), the normal limit for hose length in shotcrete construction is about 100 feet, but hoses as long as 500 feet have been used. Other sources indicate that the practical limits for hose lengths are 200 feet vertically and 500 feet horizontally from the equipment. The optimum nozzle pressure lies within a range of 25 to 75 psi, the higher pressures being more appropriate for heavy construction.

There are many shotcrete structures having walls from 14 to 40 feet high and from 5 to 8 inches thick, depending on the type of building and the city building code. Column and beam sizes depend on the structural design and the load to be carried.

While the average wall form for conventional concrete requires 6 board feet for double forms, the backing for the shotcrete wall requires less than 1.5 board feet per square foot of form surface. This amounts to a lumber saving of about 75% and is reflected in the use of fewer studs. Where 1-inch-thick lumber is used, the studs are placed at 28-inch centers instead of the closer spacing required for conventional concrete. Where plywood panels are used for backing (e.g., panel effects), studs are placed at 30- to 36-inch centers. The heavy wales used on concrete form construction are eliminated. Light wales are placed in position at the bottom, halfway up, and at the top, except in cases of extreme heights; the backing has sloping braces of two-by-fours where necessary.

Several years ago BuDocks authorized the construction of 18 ammunition magazines at the Naval Ammunition Depot (now Naval Weapons Depot), Concord, California, using fine shotcrete and found that formwork cost was 40% less than that required for conventional concrete.

In building the form, every effort must be made to have it rigid enough to produce perfectly flat surfaces and heavy enough to support the shotcrete. Scaffolding is required during gunning operations, but since a scaffold is needed by electricians, plasterers, and other tradesmen, its erection does not add any cost to the shotcrete method. A single curtain of steel reinforcement is usual for a standard 6-inch-thick wall; if an 8-inch-thick wall is desired, two curtains of steel are used. Steel design conforms to that used for conventional concrete. Steel curtains are supported from the single wall backing, and it is vital that the steel be fastened rigidly to eliminate vibration and insure proper embedment in the shotcrete. Column and beam steel are placed in position at the same time as the wall steel. Horizontal or vertical alignment guides of about No. 20 steel piano wire (also known as ground wires) are stretched along the face of the wall so that the shotcrete may be screeded to assure uniform wall thickness and true alignment.

Shotcrete is often used in the construction of walls in single-story steel-frame industrial buildings. Columns along the walls of such buildings are usually spaced at 16-foot intervals, are frequently steel H sections with the flange sides running parallel to the direction of the wall, and usually support a roof system of steel truss and purlin design. The wall design commonly includes a horizontal band of shotcrete extending from the footing level to the bottom of the window level; this is followed by a horizontal band of window sash of variable height; the upper section of the wall consists of another horizontal band of shotcrete which extends to the roof line. The typical shotcrete wall of an industrial building is 2 inches thick. Plywood forms used for walls may be considerably lighter than is normally specified for concrete construction, because the shotcrete is deposited as a thin layer over a considerable area of the form; this tends to stiffen the form before the remainder of the shotcrete is gunned into place. The forms are placed between the structural supporting members; they may be reused as many as ten times and insure a satisfactory wall-surface texture. Customary fabric reinforcement is 4- by 4-inch mesh of No. 8 wire or 3- by 3-inch mesh of No. 10 wire. These reinforcing fabrics are usually galvanized steel.

In wall construction, the shotcrete should be applied in alternate bays or strips, each about 20 feet wide, to allow for initial shrinkage before the intermediate bays are shot. If rainy weather is encountered during the construction, the shotcreting should be done under tarpaulins which may be stretched over portable wooden or metallic frames. Wall construction joints should be made by running the end of a day's shotcrete work out to a feathered edge for a distance of about 12 inches. The next morning the new work is joined to the previous work after a thorough cleaning and wetting of the feathered end.

If the nozzleman shoots at an angle considerably less than 90 degrees, the shotcrete will build up in ruffles as does a sandy river bottom and will not be uniformly dense; an excessive amount of rebound will also result. It is desirable, but not always possible, to have only one layer of reinforcement in a shotcrete wall section; this tends to keep the rebound to a minimum. Wire-fabric reinforcement is preferable to steel bars. If bars must be used, they should be round, because square bars tend to create pockets of rebound material (triangular in cross-section) adjacent to and behind the bars; such pockets contain practically no cement. When encasing bar reinforcement, the nozzle is held so as to direct the shotcrete behind the bars from both directions. Each side of the bar is shot separately. Rebound is blown off with an air jet. No rebound should be allowed to accumulate on the work or in the crevices to be filled.

When successive layers of shotcrete are applied, each layer is lightly broomed to insure a perfect bond with the following layer; any underlying layer that is hardened must be carefully cleaned and dampened before applying the subsequent layer. Walls 6 inches thick require at least two layers of shotcrete; thicker walls require three or more applications.

Proper curing is vital and prevents drying due to strong wind or solar heat. Moist curing for at least 7 days after the shotcrete is deposited is necessary; this can be accomplished by a gentle water spray during the first 16 hours (or more) after gunning, followed immediately by an application of liquid curing (sealing) compound although protective covers may be used to prevent drying; the work must be damp when the curing compound is applied; using water spray to modify the surface texture of newly deposited shotcrete is undesirable. If preferred, burlap can be suspended against the surface and kept continually wetted for at least 7 days. A dry tarpaulin covering new shotcrete work does not constitute moist curing.

The thickness to which it is practicable to deposit shotcrete outward from the vertical or horizontal form surface, without respective sloughing or sagging, depends to some extent on the support offered by the steel-fabric reinforcement. Placement of a 3-inch-thick course in one continuous operation, by gunning back and forth over the surface to be covered, is usually feasible. If the work requires more than a 3-inch cover, the operator should move to another area after placing about 2.5 inches of shotcrete; the work at the first location should be resumed after the shotcrete there has set sufficiently to eliminate all danger of slough or sag. In the case of a flat vertical surface, a 3-inch-thick layer of shotcrete can be applied with prevailing equipment at a rate of 20 to 35 square yards per hour, depending on degree of rebound. Wall areas should be shot from the bottom up because the reinforcing fabric yet to be gunned is free of rebound. In applying shotcrete to floor areas that adjoin slopes or perpendicular walls, the best practice is to shoot at least 3 feet of slope or wall integrally with the floor. This method precludes poor laps in joints along the intersection of wall and floor, because the rebound will fall below the point where the lap is to be made.

Shotcreting should not be done when the ambient temperature is below 38°F. At low temperatures, the shotcrete work must be covered with tarpaulins to protect it against freezing. Care must be taken, when working at low temperatures, that no frost exists in the shotcrete gunned during the previous day and to which the new shotcrete is to be bonded. The previously applied shotcrete should be warmed by any of the various means employed in winter building construction; the cold concrete surfaces must be prepared to receive warm concrete.

In average wall construction, shotcrete is placed at a rate of 15 to 20 cubic yards per day. In average-size buildings that require about 100 cubic yards of shotcrete, the walls, columns, and beams are normally completed in about 2 weeks. Placement of shotcrete is more expensive per cubic yard than conventional concrete, and any savings in material and labor are reduced accordingly. Nevertheless, the shotcrete process can be expected to result in a net saving of at least 20% in the total cost of the average wall-building job. Furthermore, the speed of shotcrete construction allows the contractor to spend 5 or 10 days erecting the single form, the scaffolding, and placing the steel; his crew is then free to move on to other jobs. Formwork is normally removed about 48 hours after the shotcrete has been gunned into place. In the case of conventional concrete construction, the contractor's crews are usually held on the job; while concrete crews are filling one form, other crews are either stripping forms from previously placed walls or are erecting additional forms for higher walls.

The protection afforded when shotcrete is applied to the structural steel of a building, as a means of resisting the effects of fire, is a worthwhile attribute. Such protective material suffers little damage and can be applied easily and cheaply. A relatively thin layer means less weight, which implies less material and labor than are involved in protective brick or tile cover. Less weight reduces the dead load sustained by the structural frame; less dead load is reflected in lighter beams, girders, and columns, and smaller foundations. Another reason for encasing structural steel in shotcrete is to prevent corrosion of the steel. The impact of gunning the surface of the structural member insures excellent adhesion of the shotcrete and precludes development of an entrapped air film that nearly always occurs with conventionally placed concrete. The matrix of cement paste and very fine aggregate particles is driven tightly against or even slightly roughens the surface of the steel by the incessant ramming of the particles of oncoming material, thus improving the anchorage of the matrix. Theoretically, this ramming action, which drives each aggregate particle deeper into the matrix, should make shotcrete less permeable to moisture and consequently better able to resist the destructive action of repetitive freezing and thawing than conventionally placed concrete.

In 1920 the eight-story Traylor Building at Philadelphia, Pennsylvania, was constructed of shotcrete. Every exterior hollow 12-inch-thick shotcrete panel consists of an inner and outer shell, each slightly more than 2 inches thick, and four shotcrete studs in each panel. The design was approved on the basis of the conclusions and recommendations made by the Underwriters Laboratories (Robinson et al, 1922). In this building, all of the interior partitions are also constructed of shotcrete. The cost of erecting such a 12-inch-thick shotcrete hollow wall was about 60% of that for a 13-inch-thick brick wall. The 2-inch-thick shotcrete partitions cost about 40% less than 9-inch-thick common-brick partitions.

"The cost of Gunite per cubic foot," according to Moran (1938), "is about three times that of concrete, but the safe compressive stress is also about three times that of concrete. Thus a compression member can be designed of equal strength and cost, but one third of the weight." He declared that the covering capacity of the Cement Gun, under favorable circumstances, is between 75 and 100 square yards per day per inch of Gunite thickness. He also declared that since the cost per cubic foot is so high, Gunite is not a popular method for ordinary building construction. There are difficulties in obtaining an even color and texture, because thin deposits are very susceptible to weather conditions at the time of deposition; ordinary troweled finishes do not reveal as much color variation. If Gunite is used as a substitute for difficult constructional repair methods, the monetary saving often is about seven times the actual cost of the Gunite repair, provided the basic defect in the structure is first removed as a means of preventing recurrence of the trouble.

According to Hoffmeyer (1965), premixed-wet shotcrete is cheaper per square foot than conventional concrete when wall thicknesses are 4 inches or less, but conventional concrete is cheaper when walls are 10 inches or more in thickness. Excluding steel reinforcement, premixed-wet shotcrete cost $45 per cubic yard and conventional concrete cost $20 per cubic yard in the recent construction of a church in Minnesota.

Shotcrete incorporating magnetite aggregate has been used in constructing radiation shields at Hanford, Washington (Hume, 1960). Comparative studies for 175 cubic yards showed that the cost of heavyweight shotcrete was $232 per cubic yard in place, whereas conventional concrete construction or prepacked concrete construction would have been $242 per cubic yard in place.

ENGINEERING PROPERTIES

Though shotcrete has been in use for more than half a century, there is considerable difference of opinion regarding its in-place characteristics. Another difference of opinion is concerned with whether cores drilled from the structure or from a test panel are more desirable than cylindrical test specimens made by gunning hardware-cloth molds.

Thos. J. Reading (1965) has stated* that the following values are usually assumed for hardened shotcrete at age 28 days: compressive strength, normally 4,000 psi, maximum 6,000 psi; flexural strength, normally 500 psi; and water absorption, normally 6 to 7% (by weight).

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*Private communication of 4 Mar. to W. R. Lorman.

According to Harald Omsted (1963)*, the structural engineers at the Office of the Los Angeles City School District assume that shotcrete having a compressive strength of 3,000 psi has the same physical properties as conventional concrete of equivalent strength. They realize that this assumption cannot be valid, although it has proved to be quite practicable; for instance, they suspect that the bond between steel and shotcrete may be less than that between steel and conventionally cast concrete, because slight pockets tend to form in the shotcrete (at the rear of the steel reinforcement) as the result of rebound.

Principal Test Data

Technical papers dealing with shotcrete construction are abundant, but those concerned with the fundamental physical characteristics of hardened shotcrete are relatively limited. There are six comprehensive investigations considered outstanding, and therefore these are reviewed chronologically and before the other experimental results.

The first laboratory investigation of the physical characteristics of Gunite was conducted in 1911 under the direction of Chapman (Anon., 1912; Weber, 1914). The test data show that strength (compressive and tensile) and bond of Gunite are greater, and permeability, voids, and moisture absorption are less, than corresponding properties of conventionally placed mortars. The cement-aggregate ratio (C/A) of the various mixtures ranged from 1:3 to 1:9, by volume, using sand having a 0.125-inch maximum particle size. Test ages were 7, 28, and 60 days. With respect to engineering properties, the typical values of hardened Gunite compared to those of hardened manually applied mortar may be condensed as follows with Gunite the initial entry in each case:

Property	C/A	Value
Tensile strength	1:3	1.74
	1:4	1.80
Compressive strength	1:3	1.70
	1:4	2.40
Voids	1:3	0.66
	1:4	0.67
Permeability	1:3	0.15
	1:4	0.05

*Private communication of 12 Sept. to W. R. Lorman.

Property	C/A	Value
Absorption	1:3	0.72
	1:4	0.53
Bond to steel	1:3	—
	1:4	1.27
Bond to hard brick	1:3	—
	1:4	1.42

These apply to laboratory results obtained at age 28 days, except for the voids data which are valid for age 60 days.

In 1918 the National Bureau of Standards (NBS), in collaboration with the U. S. Shipping Board, which was interested in developing shotcrete hulls for ships and barges, conducted a test series (Collier, 1918) to determine the range in compressive strength and modulus of elasticity. The slabs, representing various mix proportions, and shot either horizontally or vertically, were sawed into 384 prisms which were tested at age 90 days. Some slabs incorporated aggregate as large as 0.500 inch. The investigation showed that a well-graded mixture, having a maximum-size aggregate of 0.250 inch, produced the best results. The data indicate that the compressive strength of shotcrete at age 90 days is about 4,700 psi if the C/A (by volume) is 1:2.0, about 4,500 psi if the ratio is 1:2.5, and about 4,000 psi if the ratio is 1:3.0. The modulus of elasticity (E) test data show the average values at age 90 days as follows:

C/A (by volume)	Average E (psi)
1:2.0	5.4×10^6
1:2.5	4.8×10^6
1:3.0	4.7×10^6

Laboratory and field test data by Stewart (1931) indicate that Gunite strength bears a definite relation to the nozzle velocity at which it is shot; using a 0.75- or 1.00-inch-diameter nozzle, a velocity of 375 fps produces maximum strength. He found that a water-cement ratio (W/C) of 0.55 assures as stiff a mixture as is practicable to shoot and recommended a W/C range of 0.55 to 0.65 (by weight). The fineness of the sand also bears a definite relation to the strength. The effect of these three factors on strength, moisture absorption, and rebound, as indicated by the results of over 500 test specimens (cores and prisms), is shown graphically in Stewart's paper. The low limit for compressive strength is 4,000 psi at age 7 days, if the nominal C/A is 1:3.5 and if fair quality sand is used. Subsequent observations by Stewart (1933), using a 1.25-inch-diameter nozzle, showed that Gunite of maximum strength and density is obtained with an air velocity of 510 fps and with the nozzle held about 4 feet from the work. The average mix proportions were 1:3.8, by volume, with the sand containing 4% moisture by weight. The strength of the Gunite increases as the water content decreases, but there is a practical limit to the dryness of the mixture; 10% moisture content (equivalent to 4 gallons per bag) is a practical minimum for Gunite under the steel reinforcement, and 9% moisture (equivalent to 3.5 gallons per bag) is practical for Gunite above the reinforcement. The average compressive strength at age 7 days extended from 4,000 psi, for a C/A of 1:6, to 7,000 psi, for a C/A of 1:3. When a particularly hard sand was used in conjunction with a C/A of 1:3.5, the 7-day compressive strength varied between 7,000 and 10,000 psi.

USBR experiments were conducted at Arrowrock Dam by Studebaker (1939) during the period 1937 - 1939, to develop quality control of the Gunite used in constructing the spillway channel. The C/A was 1:4.5, by weight, which included 3% diatomaceous earth as an admixture. The W/C, by weight, of the Gunite used in lining the spillway sides (having a slope of 0.5:1) was 0.57. For vertical and overhanging surfaces, the Gunite had a W/C of 0.50. His investigation led to the following: (1) strength tests are impractical in the control of Gunite, because no relation has been found to exist among strength, durability, and economy of Gunite, and because strength data become available too late for timely corrective action on the job; (2) the W/C of a Gunite test specimen cannot be determined accurately; (3) irregularities in fabricating Gunite test specimens have a greater effect on strength than do quality control factors; (4) carving small cylindrical test specimens of uniform diameter from unhardened Gunite is impractical, because some fracture of the specimen always occurs; (5) drying shrinkage of Gunite is directly proportional to the percentage of water in the mixture and inversely proportional to the percentage of cement; (6) durability is promoted by low water content and high cement content; (7) diatomaceous earth as an admixture requires the use of additional mixing water to attain a certain consistency, consequently causing more shrinkage, and is not recommended; (8) lean mixtures incorporating fine sand having a fineness modulus (FM) of 2.50, shrink more than do rich mixtures incorporating coarse sand (FM of 3.36); (9) for a given sand, and with consistency constant, the yield (pounds of Gunite per pound of nominal mixture) is practically constant regardless of mix proportions; (10) fine-sand mixtures insure greater yield than coarse-sand mixtures if consistency is held constant; (11) the wettest consistency at which fresh Gunite is stable is that attainable with coarse-sand mixtures; (12) for a constant consistency, using a given sand (FM of 2.49, 2.96, or 3.26), the percentage of rebound is nearly constant regardless of C/A (1:3 to 1:6, by weight); (13) within the range of ordinary consistencies and all other conditions constant, the percentage of rebound is inversely proportional to W/C; (14) high W/C promotes economy by reducing the percentage of rebound and cement content; (15) for greatest economy, Gunite should be shot at a W/C that is compatible with impending sloughing; (16) given a W/C compatible with required strength and durability, the initial mix proportions should be such that the Gunite will have the given W/C when it is sprayed into place at a consistency for which sloughing impends; and (17) the greater the durability, the greater the material cost.

The physical properties of Gunite were studied at the University of California 25 years ago (Campbell et al, 1940). The interrelations of cement type, cement-aggregate ratio, aggregate gradation, and consistency of fresh Gunite, and their effects on the shrinkage and flexural strength of hardened Gunite, constituted the main phase of the work. Changes in aggregate gradation and mix proportions from the nominal (as designed) to the actual (after gunning) were considered as part of the investigation. Nozzle velocity (400 fps) of the Cement Gun and curing conditions (28 days in fog) were constant, but specimens older than 28 days were stored in 50% relative humidity (RH) until tested. Shrinkage comparisons were made at age 60 days, using 108 length-change bars. Analysis of the data showed that the actual aggregate gradation was about 20% finer than the nominal gradation, regardless of original fineness modulus (FM) of the sand; the sands used were coarse (FM of 2.96), intermediate (FM of 2.66), and fine (FM of 2.35). Changing the FM of the nominal gradations from 2.96 to 2.35 had no practical effect relative to changing the actual W/C of the in-place Gunite. Throughout this range of FM, varying the C/A, the W/C, or cement type did not noticeably affect actual gradation of the in-place Gunite. Rebound was accompanied by a small amount of cement paste, so the in-place mixture was richer than the nominal mixture (i.e., the actual C/A was larger than originally planned).

Note that the relation between actual W/C and actual C/A always is an inverse one when using premixed-dry shotcrete, because the nozzleman tries to maintain uniform consistency visually by changing the water content as the actual C/A increases. Where either Type I or III cements were used, the actual W/C was slightly higher than the nominal W/C, but if high-silica cement was used, the actual W/C was lower than nominal. Increase in actual C/A, due to rebound, became higher as the gunned mixture became drier, regardless of which of the three cements was used. Plain Gunite made with high-silica cement exhibited less shrinkage than companion Gunites made with either Type I or III cement; shrinkage increased with increasing W/C or C/A. Reinforced Gunite made with high-silica cement cracked less and more slowly than companion Gunites made with either Type I or III cement; minimal cracking occurred because the materials shrank less, and since it crept more it allowed gradual release of tensile stress; in Gunites containing Type I or III cement, the release of stress was comparatively sudden. The flexural strengths of 648 beams of plain Gunite were determined at age 28 days to compare the effects of certain variables; the data show that excellent strength was developed with any of the three cements used; flexural strength increased with decreasing W/C and increasing C/A.

The Portland Cement Association (PCA) (Litvin and Shideler, 1965) has been conducting an extensive investigation of shotcrete since 1960. So far, two phases of the program have been completed and provide for 38 shotcrete mixtures. In the first phase, laboratory data were developed using shotcrete wallettes produced at various construction sites and shipped to the PCA laboratories. In the second phase, wallettes were gunned in the PCA laboratories using several types of equipment with various mix proportions, three gradations of aggregate, and a few admixtures. The engineering properties of nonreinforced shotcrete studied so far are strength (compressive and flexural), Young's modulus, shrinkage, creep, absorption, freezing - thawing resistance, and permeability. The test data indicate a separation of the mixtures, on the basis of physical properties, into two groups as follows: (1) wet-mixed mortars having a C/A of 1:3.00 (by weight) and 1:3.00, 1:4.50, or 1:6.00 (by volume); and (2) dry-mixed mortars having a C/A of 1:3.00, 1:4.00, 1:5.00, or 1:6.00 (by volume), dry-mixed concretes having a C/A of 1:4.00 (by volume) and either 1:4.26 or 1:6.08 (by weight), and wet-mixed concretes having a C/A of 1:4.00 (by volume) and 1:2.72, 1:2.79, 1:2.87, or 1:4.65 (by weight). The maximum-size aggregate was 0.750 inch. The average 28-day compressive strength of 3-inch cubes (while moist) in Group 1 ranged between 3,100 and 7,900 psi, and in Group 2 ranged between 6,100 and 12,900 psi. The average 28-day flexural strength of 3- by 3- by 12-inch prisms (in moist condition) ranged between 580 and 780 psi for Group 1 and 600 to 1,400 psi for Group 2. Young's modulus (moist condition) for Group 1 ranged between 2.6×10^6 and 4.4×10^6 psi at age 28 days, whereas Group 2 ranged between 3.2×10^6 and 5.8×10^6 psi. At age 28 days, the relation between Young's modulus and moist-condition compressive strength (between 3,000 and 11,000 psi) was found nearly linear for any of the mixtures investigated in the first phase. On the basis of moist condition at age 28 days, the flexural strength of Group 1 mixtures was between 12 and 21% of the compressive strength; for Group 2 the range was between 7 and 11%. The relation between compressive strength and net W/C (actual in-place) was found curvilinear for both phases, higher strengths being associated with lower W/C. In the first phase at age 6 months, the shrinkage of Group 1 specimens varied between 0.135 and 0.150%, and in Group 2 the variation ranged from 0.060 to 0.105%; these valuesare higher than those usually occurring in conventional concrete. In the first phase, the creep rate of Group 1 shotcrete was found greater than that of Group 2, and the ultimate creep (due to sustained compressive stress of 1,000 psi beginning at age 28 days) probably is about seven times that of Group 2 shotcrete; high W/C is associated with high creep of shotcrete. Generally, shotcrete produced by the dry-mix process demonstrated greater durability in the freezing - thawing test than did that produced by the wet-mix process; nevertheless, in the first phase the purposeful entrainment of about 10% air in a wet-mixed mortar (Group 1) insured from four to 14 times the resistance (to 350 cycles of alternate freezing and thawing) obtained with companion shotcrete mixtures containing about 2% air at the time of production. Percentage of absorption and dry unit weight (both at age 7 days) are good indicators of the general performance of shotcrete; in the first phase the average moisture absorption of Group 1 was 13% and of Group 2 was 6%, whereas the corresponding average densities (in dry condition) were 124 and 137 pcf; if both phases are considered, in Group 1 the average absorption was 10% and the average density was 126 pcf, whereas in Group 2 the corresponding values were 7% and 137 pcf. Permeability test data were too erratic to be meaningful. Dry-mixed shotcretes incorporating coarse aggregate suffered reductions in FM between 8 and 21%, as the result of rebound.

Density

The average unit weight of hardened plain (nonreinforced) shotcrete lies between 140 and 145 pcf when ordinary siliceous aggregates are used; that of hardened plain concrete containing identical aggregate lies between 145 and 150 pcf. The density range of plain shotcrete, however, can extend from 120 to 160 pcf, depending on maximum size of aggregate and consequent rebound, mix proportions, and procedural variations during placement.

Swenson (1913) concluded that the amount of voids in ordinary Gunite varies between 50 and 75% of that found in conventionally placed mortar.

Hardened lightweight shotcrete ranges from 90 to 120 pcf if regular lightweight aggregate is used, but if special lightweight aggregate is employed, the unit weight of hardened insulation shotcrete ranges from 40 to 90 pcf. Hardened heavyweight shotcrete, incorporating metallic aggregate, ranges from 160 to 230 pcf.

Rebound

Gillespie and Culliton (1924) investigated the rebound of Gunite shot against a steel girder. Their data indicate that mixtures made with coarse sand result in four times as much rebound as those made with fine sands.

There is a loss of mixing water due to rebound and also due to atomization; Stewart (1933) found that the latter may be about 1.5 gallons of water per bag of cement when using a 1.50-inch-diameter nozzle. Rebound increases with higher hose pressure and nozzle velocity. On overhead work which utilizes a relatively dry shotcrete, the rebound tends to be greater than with the relatively wet mixtures applied to vertical surfaces. Studebaker (1939) found that rebound is inversely proportional to the W/C within the range of ordinary shotcrete consistencies.

A recent investigation (Anon., 1962) has resulted in additional information in this area. Rebound increases inversely with cement content and appears to be independent of aggregate gradation. If shotcrete discharge is horizontal, the rebound is greater than if the discharge is vertical. In-place shotcrete has a tendency to spall when the discharge is horizontal, the layer is thicker than 2 inches, and the cement content is low. Rebound causes variations in the original mix design; if the original C/A is 1:5 or 1:3, the in-place ratios range, respectively, between 1:3 to 1:4 and 1:2 to 1:2.5. Even with a skilled nozzleman controlling the mixing water, the water content of in-place shotcrete (premixed-dry) varies about 11%.

Compressive, Flexural, and Tensile Strength

The relation between strength and W/C of shotcrete is similar to that for concrete and mortar. Compared with conventionally placed mortar having an equivalent C/A, fine shotcrete exhibits greater compressive and flexural strength because the spraying method allows the use of a lower W/C. Conventional concrete of 1:2:4 mix proportions exhibits an average compressive strength of 2,000 to 3,000 psi at age 28 days; conventional mortar of 1:4 mix proportions, 1,500 to 2,000 psi at age 28 days; and fine shotcrete of 1:4 mix proportions, 5,000 to 7,000 psi at age 28 days.

Swenson (1913) concluded that the compressive strength of pneumatically applied mortar is 20 to 70% better and the tensile strength is 20 to 25% better than that attainable with manually placed mortar.

Caples (1916) conducted tensile strength experiments with Gunite having a C/A ratio of 1:4 (by volume). The mortar was gunned into briquette molds, and the specimens were cured in water until tested. The averages show tensile strengths of 160 psi at age 7 days and 360 psi at age 28 days.

According to Collier (1918), in 1917 McKibben of Lehigh University undertook an investigation of the modulus of rupture of Gunite. Some slabs were shot horizontally and some vertically, cement-sand proportions were 1:3 and 1:4 (by volume), and slab thicknesses were 2 and 4 inches. The slabs were shot either in one layer or in several 1-inch layers and at various intervals ranging from 1 to 24 hours. At age 28 days, using center-point loading, the average flexural strength of horizontally shot slabs ranges between 210 and 620 psi; at age 90 days, the range extends from 310 to 800 psi. Information regarding width of slab and length of span is unavailable.

In 1919 at Paris, France (Bousquet, 1920), a laboratory investigation was made of the comparative characteristics of Gunite and manually cast mortar. The results show that the flexural strengths of Gunite at ages 7 and 28 days are about three times those of hand-placed mortars. At age 7 days, the compressive strength of Gunite is two times that of hand-placed mortar, but at age 28 days the ratio drops to about 1.2 in favor of Gunite. Tensile-strength tests at ages 7 or 28 days, using briquette test specimens, show that Gunite is about 1.5 times as strong as hand-cast mortar.

In conjunction with the use of interlocking shotcrete panels used in the construction of an 8,800-foot-long sea wall, compressive strength tests were conducted by Fuller at Lehigh University in 1925, according to Bryan (1926). The 19 test specimens, each 2 by 2 by 8 inches, apparently were sawed from the panels. The C/A of this shotcrete was 1:3 (by volume), and the maximum-size aggregate was 0.375 inch. At age 56 days, the average compressive strength was 7,500 psi.

In an investigation (McCullough, 1933) of shotcrete used for restoring bridges in Oregon, tests were made on five 1.5-inch-thick shotcrete slabs, each 8 by 4 feet in area. Each slab was placed over knife-edge supports about 4 feet apart and subjected to center-point loading. The average compressive strength, presumably at age 28 days, was 8,000 psi, based on a range from 6,400 to 9,800 psi.

The petrographic quality and the freedom from organic impurities are important factors in choosing sand for shotcrete. Using a cement - sand ratio of 1:3, Pearson (1933) found that with a single-washed common sand, the 7-day compressive strength of Gunite averaged 3,700 psi. All test specimens were cubes sawed from Gunite slabs. Duplicate tests, using double-washed common sand, showed that the 7-day compressive strength averaged 6,000 psi. Additional tests were made using double-washed select-grade sand, and (all other factors being equal) the average 7-day compressive strength became 10,000 psi. He conducted further tests, using plain concrete blocks and reinforced-concrete stanchions, all of which served to prove that considerable extra strength can be imparted to a relatively weak concrete by proper encasement in Gunite. Such a Gunite "cover" can be applied regardless of the complexity of the structural design of the original concrete.

The dome of the Hayden Planetarium at the American Museum of Natural History in New York, New York, is of shotcrete construction. Similar domes are in use in planetariums in Philadelphia, Chicago, and Los Angeles (Griffith Observatory). In the case of the Hayden Planetarium, specifications called for Gunite having a C/A of 1:3 and capable of developing a compressive strength of 2,000 psi at age 4 days and 3,500 psi at age 28 days. Eight test slabs (Bertin, 1935), each 20 by 6 by 1.75 inches, were cured under the same conditions as the structure and represented cement:sand:pea-gravel proportions of 1.0:2.1:1.4 (by volume). The test data reveal average flexural strengths at ages 2, 4, and 14 days as, respectively, 720, 650, and 870 psi. The average compressive strengths at these ages are, respectively, 3,900, 3,250, and 5,950 psi.

Withey and Aston (1939) describe tests made in 1936 at the University of Wisconsin by Culbertson and Deno on 53 Gunite prisms, each 3 by 3 by 28 inches, representing C/A of 1:3, 1:4, and 1:5. The modulus of rupture ranged from 630 to 1,030 psi at age 28 days. Compressive strength, using modified cubes from the flexural tests, ranged from 4,750 to 11,100 psi at age 28 days. All test specimens had been moist-cured 7 days and then stored in laboratory-room-dry air for 21 days.

A shotcrete compressive strength of about 12,000 psi at age 30 days was observed (Moran, 1938, 1939) in a full-scale test of a 2-inch-thick reinforced arch having a 12-foot span, but no information concerning mix proportions is shown in the references cited.

In the experiments by Staley and Peabody (1946), also discussed in the next two subsections ("Elasticity" and "Volume Change"), Gunite and concrete were compared. The C/A of the Gunite was 1:4, but W/C was not determined. The concrete, which contained 0.750-inch maximum-size aggregate, had a W/C of 0.50 by weight and mix proportions of 1:2.1:3.2 (or C/A of 1:5.3). The compressive strengths at age 28 days of 4-inch-diameter by 8-inch-high Gunite and 6-inch-diameter by 12-inch-high concrete test specimens averaged, respectively, 4,900 and 4,500 psi.

The USBR conducted laboratory tests (Crosby, 1948) of Gunite made with very fine sand (containing 15% silt) having an FM equal to 1.18; various values of C/A extended from 1:8 to 1:4, by weight. At a C/A of 1:4 the compressive strengths at ages 7, 28, and 90 days were from 33 to 44% less than those obtained with companion Gunite test specimens which were identical except for a sand FM of 2.48.

Compressive strengths of 10,000 psi at age 7 days have been attained with shotcrete test cubes having a C/A of 1:3 (by weight) (Kelsall, 1951).

Using Type II cement, with sand having an FM of 2.73 and a C/A of 1:4.3 (by weight), the compressive strength of the Gunite used in the first structural experiment at NCEL (Wiehle, 1953a) averaged 2,490 psi at age 7 days and 4,540 psi at age 28 days. In the second structural experiment (Wiehle, 1953b) at NCEL, the compressive strength averaged 1,290 psi at age 1 day, 3,190 psi at age 7 days, and 5,990 psi at age 28 days. Flexural strength at age 9 months, after outdoor storage adjacent to the shotcrete structure, averaged 770 psi. The sand-cement ratio was 5.5, by volume, and the FM of the sand was 2.81.

One reference (Anon., 1958) tabulates several shotcrete mixtures and corresponding 28-day compressive strengths as follows:

C/A (by volume)	Compressive Strength (psi)
1:4.0	4,000
1:4.5	3,000
1:5.0	2,500
1:6.0	2,000

According to this source, under proper conditions 60% of any of the above 28-day compressive strengths may be obtained at age 7 days.

The Atomic Energy Commission authorized a laboratory investigation (Hume, 1960) of heavyweight shotcrete incorporating magnetite aggregate, having an FM of 1.75 and specific gravity of 4.86, and using 53 test cylinders, each 6 inches in diameter by 12 inches long. The average unit weight was 235 pcf. The average compressive strengths were 2,150, 4,190, and 5,180 psi at 3, 14, and 28 days age, respectively.

Shotcrete tests made in Germany (Haas, 1962) showed an average tensile strength of 560 psi and, using 3-inch test cubes made with a C/A of 1:3 (by volume), an average compressive strength of 7,500 psi at age 1 month.

Compressive strength, which increases as the cement content increases, appears to increase when coarse aggregate is used in the shotcrete (Anon., 1962a). However, when successive layers alternately incorporate finer and coarser aggregate, there seems to be some uncertainty regarding the strength advantages of using larger aggregate. The direction of gunning and the number of layers affect compressive strength very little. In Ostlund's investigation, the average compressive strength at age 28 days was 6,400 psi (deviation 12%) for mixtures having a C/A of 1:5, 7,400 psi (deviation 13%) for those having a C/A of 1:4, and 7,450 psi (deviation 6%) for those having a C/A of 1:3. These compressive-strength values were determined by using 8-inch test cubes made in conjunction with shotcrete panels 7.5 feet square.

Lightweight shotcrete has often been used for encasing steel beams. Recently it was used in buildings of steel-frame construction and where floors rest on steel decks (Anon., 1962b). Beams were wrapped in wire fabric which was tied to the steel decks. At age 28 days the minimum compressive strength was 3,000 psi, using a 1:4.5 mixture of cement and lightweight aggregate (expanded shale).

Since the Jetcrete investigation in 1949 (see the subsection herein entitled "Durability"), the Army has been involved with only one shotcrete experimental project, and that was concerned (Anon., 1965) with lining walls of several 10-foot-diameter spherical cavities mined in massive basalt. Using premixed-wet fine shotcrete (slump, 3.0 to 3.5 inches; common sand; Type III portland cement; W/C of 0.54, by weight; C/A of 1:3, by weight), the average compressive strength of 18 test specimens (2-inch cubes) at age 22 days was 8,200 psi.

The Army uses shotcrete to renovate the linings (Anon., 1948, 1965) of the Soo Locks at Sault Sainte Marie, Michigan. In the case of a 750-foot-long lock wall 50 feet high, shotcrete was applied in one layer 4 to 5 inches thick, and reinforcement was 4- by 4-inch (No. 6 by No. 6) wire fabric. Mix proportions are 12 bags of Type IA cement per cubic yard of Lake Superior sand, which has an FM of 2.4. Specifications require a 28-day average compressive strength (using test cylinders) of 6,500 psi; test data usually indicate an average compressive strength between 7,000 and 8,000 psi. Following shotcreting, a 14-day curing period is required of which the first 10 days are with full heat (40 to 45°F from a central steam plant normally used to keep the lock gates ice-free during early spring and late fall shipping operations) followed by 4 days of gradual cooling.

Lightweight shotcrete, premixed-dry with Type I cement and expanded shale aggregate (having a maximum size of 0.375 inch and graded to conform to ASTM Specification C330-60T*) has been investigated by Barnard and Tobin (1965). The following table shows the compressive-strength range that can be expected at age 28 days:

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*See references

C/A (by volume)	Cement Factor (bags/cu yd)	Yield (cu ft/bag)	Compressive Strength (psi)
1.0:3.0	9.8	2.8	4,800 - 6,000
1.0:3.5	8.9	3.0	4,000 - 5,000
1.0:4.0	8.0	3.4	3,500 - 4,200
1.0:4.5	7.4	3.6	3,000 - 3,500
1.0:5.0	6.9	4.0	2,500 - 3,000

Elasticity

The slabs investigated by McCullough (1933) (see subsection herein entitled "Compressive, Flexural, and Tensile Strength") exhibited an average modulus of elasticity of 4.7×10^6 psi based on a range from 3.8×10^6 to 5.4×10^6 psi at age 28 days.

The observance of 4- by 4- by 24-inch test specimens by Staley and Peabody (1946) (see the subsections herein entitled "Compressive, Flexural, and Tensile Strength" and "Volume Change") resulted in elasticity data that are of value in studying shotcrete. Young's secant modulus was computed from elastic strains that occurred during loading; Young's tangent modulus was determined sonically before loading. The range of secant modulus at high stress was 3.1×10^6 to 4.5×10^6 psi for Gunite and 3.0×10^6 to 4.5×10^6 psi for concrete. The average tangent modulus at high stress was 6.2×10^6 for Gunite and 4.8×10^6 psi for concrete.

Young's modulus for Gunite test specimens, made incident to Wiehle's (1953b) second structural experiment, at age 28 days averaged 5.4×10^6 psi (dynamic) and 4.3×10^6 psi (static).

The work by Haas (1962) indicates that Young's modulus ranges from 5.6×10^6 to 6.6×10^6 psi at age 28 days although he does not indicate test-specimen size.

Volume Change

Gillespie and Culliton (1924) investigated the swellage characteristics of Gunite. Each test specimen was 6.0 by 1.5 inches in cross-section and 12.0 inches long, and was equipped with gage studs to accommodate an 8-inch gage-length extensometer. The specimens were stored in water for various periods ranging from 5 to 17 days. Upon removal from storage, the specimens were measured for swellage, and the observations were as follows:

C/A (by volume)	Immersion Time (days)	Swellage (in./in.)
1:4.0	5	0.000185
1:4.0	17	0.000245
1:3.0	9	0.000212
1:2.5	12	0.000195

They concluded that the average swellage developed between the dry and saturated stages generally is 0.0002 in./in.

Staley and Peabody (1946) investigated the shrinkage and creep of both prestressed and unstressed test specimens of Gunite and of concrete during storage in 50% RH at 70°F to age 1 year. The specimens, each 4 by 4 by 24 inches, were compressively loaded in the longitudinal direction by means of steel plates fitted onto steel rods and secured by tightening nuts on the rod ends. Prestress was not maintained constant throughout the investigation, but was applied at an early age and allowed to decrease depending on shrinkage and creep. At age 10 days, the Gunite shrinkage was about 75% of the concrete shrinkage for non-loaded specimens; the maximum shrinkage was 6.5×10^{-4} in./in. for Gunite and 8.7×10^{-4} in./in. for concrete at the end of 1 year. The loaded specimens were stressed to 930, 1,500, or 2,400 psi. Strain observations of the prestressing rods were used in computing the stresses in the concrete and Gunite. After 1 year, the stresses in the Gunite were about 43% of the initial stress. After 1 year, the creep of Gunite was about 75% of that exhibited by concrete when using test specimens initially stressed to 1,500 or 2,400 psi. In the case of the low-stress specimens, the creep of Gunite was 90% of that for concrete at age 1 year.

Price (1948) indicates that shotcrete made with a sand having an FM of 2.50 exhibits greater drying shrinkage than does that made with sand having an FM of 3.25.

Haas (1962) has stated that shotcrete exhibits less drying shrinkage than does conventional mortar.

The coefficients of thermal expansion of mortars range from 5×10^{-6} to 7×10^{-6} in./in. per degree F. For cement paste, the range extends from 6×10^{-6} to 9×10^{-6} in./in. per degree F. The first and only known investigation of the thermal expansion coefficient of Gunite was undertaken by Fuller (1925) at Lehigh University. Test specimens were 8 by 12 by 1.25 inches and were sawed from a hardened slab of Gunite (mix proportions, age at test, and other pertinent data are unavailable). The range of controlled temperatures extended from 57 to 1,297°F; the temperature differentials varied between 970 and 1,237°F. The experimental data indicate coefficients of thermal expansion between 6.41×10^{-6} and 6.54×10^{-6} in./in. per degree F. As a general statement regarding any hardened shotcrete, the use of 6 millionths per degree F appears quite acceptable; this value is identical to that for average conventional concrete. The coefficient is influenced by the petrographic type of aggregate and so could lie between 4 and 7 millionths in some instances.

Sweet (1948) has shown that the coefficient of thermal expansion of concrete varies directly with the coefficient of the coarse aggregate. Furthermore, there is a general relation between the coefficient of the aggregate and the amount of silica present in the rock that is the source of the aggregate; the greater the silica content, the greater the coefficient of the rock. Therefore, the proper choice of aggregate could assure hardened shotcrete that exhibits little thermal expansion.

Thermal conductivity of shotcrete is a function of bulk density. Substantial variations in density will cause changes in thermal conductivity, a potentially serious matter with fire-insulating shotcrete.

Bond Strength

In connection with the construction of a siphon at Yorktown Heights, New York, Swenson (1913) concluded that the adhesion of Gunite is about 25% better than that of hand-placed mortar.

Bousquet's (1920) tests of bond of steel-reinforcing bars indicated that Gunite's resistance in the pullout test was 2.5 times as great as that of hand-placed mortar at age 7 and 28 days. This has been substantiated by Haas (1962) who has stated that bond of shotcrete is twice to three times greater than attainable with hand-troweled mortars. However, the earliest bond-strength data (see the subsection herein "Principal Test Data") demonstrated that bond of Gunite is barely 1.3 times that of hand-placed mortar.

According to Price (1948), shotcrete containing sand having an FM of 2.50 possesses about 10% greater adhesion (i.e., less rebound because coarse particles rebound more than do fine particles) than obtainable with a similar shotcrete containing sand having an FM of 3.25.

Permeability

With the increasing use of sprayed concrete in the construction of swimming pools, there seems to be an increasingly popular belief that shotcrete is absolutely watertight. Most of the literature discloses that the permeability of shotcrete is not appreciably less than that of well-compacted good-quality concrete placed and cured in the conventional manner. Nevertheless, according to Swenson (1913) the permeability of Gunite is 5 to 70% of that exhibited by hand-placed mortar, and moisture absorption of Gunite is 20 to 50% of that usually exhibited by hand-placed mortar.

The more dense the concrete or mortar, the more impervious to moisture in liquid or vapor phase. Ordinary concrete, if fairly thick, has sufficient density to be practically watertight. Relatively thin shotcrete has withstood hydraulic heads measured in hundreds of feet. An example is the test (Jorgenson, 1917) made at the University of California in 1917. A 1-inch-thick test specimen of Gunite was subjected to a head of 1,610 feet for 2.5 hours without indication of moisture passage, whereupon the head was increased gradually to 3,400 feet, and the specimen broke. Examination of the specimen indicated that moisture had penetrated to a depth of 0.625 inch.

In 1929, at Los Angeles, a private dwelling, designed by Richard J. Neutra, F.AIA, was built using 1.25-inch-thick shotcrete curtain walls suspended from steel framework. The building permit was granted only after tests had proved that the walls would withstand a wind pressure of about 30 psf. Such thin walls mean lower cost and a reduction in the dead load of the building; the latter item is an important factor where earthquakes occur. To convince the Los Angeles municipal building officials of the strength of the comparatively thin walls, slabs of shotcrete of various thicknesses were tested in Los Angeles laboratories. The results of all these tests are not available, but the records show (Morgan, 1930) that test specimens from 0.375 to 0.500 inch thick withstood hydraulic pressures from 300 to 690 psi. A 1-inch-thick shotcrete slab showed no signs of moisture penetration after being subjected to 690 psi hydraulic pressure for 2.5 hours; not until the water pressure was gradually raised to 1,470 psi did the specimen begin to leak and break in flexure.

Scobey (1935) advises that the tightest canal lining, and also the roughest surface, is unsmoothed shotcrete; the values of "n" in the Kutter formula range from 0.017 to 0.018 for such a finish. Trowel-finished shotcrete will have a value of 0.0135; this compares favorably with precast concrete pipe, which has a value of 0.012 or less for circular cross sections. An "n" value of 0.014 separates the smooth texture from the rough texture and is most frequently used in computations for hydraulic flow along concrete linings.

Fishburn (1942) conducted an extensive NBS investigation of 50-inch-high Gunite-faced masonry walls, each 40 inches wide and 9 inches thick, subjected to water spray which simulated wind-driven rainfall for periods as long as 5 days. He concluded that (1) Gunite-faced walls are highly resistant to water penetration and (2) 4 years of weathering causes no crazing of such walls and has no significant effect on the permeability of Gunite.

Crosby's investigation (1948) (see the subsection herein entitled "Compressive, Flexural, and Tensile Strength") indicated that Gunite's permeability is influenced by pressure and velocity during gunning and is not solely governed by W/C.

Fishburn (1958) advises that the application of a shotcrete coating, 0.75 inch or more in thickness, to the outside faces of masonry or monolithic concrete walls greatly increases their resistance to penetration of moisture. A shotcrete coating covers and seals vulnerable joints in the walls against leakage. If the coating thickness is 2 inches or more, welded-wire fabric reinforcement is necessary to reduce the possibility of large shrinkage cracks in the coating. Such shotcrete coatings do not protect the walls against leakage if the walls are severely cracked as the result of unequal foundation settlement, excessive drying shrinkage, excessive thermal changes, or any combination of these factors.

Haas (1962) states that German tests show shotcrete is less pervious to moisture than conventionally placed mortar.

Durability

Gillespie and Culliton (1924) conducted tests to compare the abrasion resistance of Gunite with that of mortar and concrete. Seven test specimens of 1:3 Gunite, six specimens of 1:3 hand-placed mortar, and six specimens of 1:2:3 concrete were inserted in a Deval abrasion machine, together with 10 pounds of Ottawa sand, and subjected to 10,000 revolutions. The percentages of wear were as follows: Gunite, 7%; mortar, 16%; and concrete, 11%.

Jetcrete, which is premixed-dry fine shotcrete, was investigated by the Army (Anon., 1949; Cook and Kennedy, 1951) for abrasion resistance. The test specimens were 24- by 24- by 2-inch slabs of plain shotcrete. Cement content was 9.5 bags per cubic yard, W/C was 0.43 (by weight), and C/A was 1:3 (by weight). Abrasion resistance was very good, as shown by controlled sandblast tests that began at age 90 days.

Statements occasionally appear in the technical literature to the effect that entrapped-air voids in shotcrete are present in larger percentages than are those in conventional concrete and, not being interconnected, help shotcrete to withstand freezing better than conventional concrete made without air-entraining admixtures. Such statements are contrary to the hypothesis explained previously (see the section entitled "General Facts About Shotcrete Construction") and are misleading.

Jetcrete also was investigated (Anon., 1949; Cook, 1951) for resistance to freezing and thawing; test specimens included 3.5- by 4.5- by 16.0-inch non-reinforced beams. The results showed that resistance to freezing and thawing was very poor (temperature range was 0 to 40°F every 24 hours, beginning at age 9 days); structural integrity was lost after 20 cycles of alternate freezing and thawing. The average Young's modulus was 6.7×10^6 psi at age 9 days.

According to Ostlund (Anon., 1962a), laboratory tests in Sweden demonstrated that shotcrete has adequate resistance to freezing in air and thawing in chloride solution. However, the type of damage is different than with conventional concrete; rather than spalling, the shotcrete tends to split along the planes of demarcation between gunned layers.

Crude oil causes severe corrosion inside steel storage tanks; most of the damage occurs on the tank bottoms where saline water settles and in the upper unoccupied spaces where moisture condenses. Gunite coatings have been found most effective

(Camp, 1948; Brannon, 1949) in preventing internal corrosion of all portions of oil storage tanks of all sizes. Though Gunite linings cost from 50 to 60% of the cost of a new tank, they have proved to be effective for as long as 15 years, whereas paints normally insure no more than 4 years of service (Oxley, 1951).

The Anaconda Copper Mining Company has used Gunite for fireproofing dozens of mine shafts in the vicinity of Butte, Montana; Norris (1919) has described the procedures utilized. On the basis of the report by Guiteras (1939), the Anaconda experience indicates that 0.75-inch-thick Gunite is ample for fireproofing underground timbers, and a C/A of 1:3 is best for such protection.

Structural Design

The use of shotcrete, especially as a constructional material for thin-shell structures, is becoming commonplace mainly because the method of construction has proved economical. Nevertheless, structural design information is meager.

It has been found by experience that ordinary shotcrete walls 2 inches thick are required for spans up to 4 feet. Walls must not be less than 3 inches thick for spans up to 8 feet.

Subsequent to the NBS tests (Collier, 1918) many structural designers requested technical information regarding amounts of reinforcement needed for various slab thicknesses under various loadings. These inquiries resulted in a series of tests directed by Fuller at Lehigh University during the period 1919 - 1920. The Lehigh tests showed that at age 28 days, reinforced Gunite, having a C/A of 1:3 (by volume), has a safety factor of 4 if stressed to 1,500 psi in flexure (the extreme fiber stress in the slab when tensile working stress in the steel-fabric reinforcement is 20,000 psi), and nearly 5 if stressed to 1,800 psi (for a C/A of 1:2.5, by volume). These values are based on results obtained with 43 slabs, each 4 feet wide, tested under third-point loading using spans of 4, 6, or 8 feet and representing slab thicknesses of 2 and 4 inches (Anon., 1920a, 1920b, 1920c, 1921; Collier, 1919; Strehan, 1921).

A series of design tables (Anon., 1920d; Williams and Strehan, 1921) show slab thickness and amount of steel reinforcement needed for various live loads. The slab thicknesses vary from 1.50 to 3.75 inches, and the percentages of reinforcement have been computed to develop the strength necessary to support live loads ranging from 30 to 200 psf. In these tables of safe loads, all computations were based on simply supported spans (ranging from 3 to 8 feet) and the value of n (i.e., $E_s \div E_c$) was assumed as 10. The current usefulness of these tables is doubtful, however, in view of the improved mechanical properties of modern steels and the higher bond stresses permitted in modern reinforced-concrete structural design.

Dischinger, in conjunction with Carl Zeiss, the photographic lens manufacturer, endeavored in 1923 to design shells on a rectangular plan (i.e., double-curved shells stiffened by vertical trusses). The difficulties of calculation were so great that the system was abandoned, and investigations were concentrated on single-curved shells stiffened at both ends. The latter was the type constructed in 1924 at Jena, Germany, for the Carl Zeiss Works and was the first full-scale shotcrete curved-shell roof of small span. The first large-scale scheme, with spans of 95 feet, was constructed in 1926 at Dusseldorf, Germany.

Shotcrete has been used more recently for shell roofs covering unrestricted areas as great as 150 by 350 feet. Curved sides and corners may be formed at no extra cost. Shells can seldom be constructed with a thickness much less than 2 inches, not necessarily for reasons of strength but because of the need for covering the steel reinforcement.

According to Snow (1947), tensile, compressive, and shear stresses must be calculate for each point on the shell and then converted to principal stresses. The magnitude and direction of these principal stresses having been determined, reinforcement is provided in these directions to take up the stresses. The method of construction adopted in the case of Zeiss is applicable to spans up to 120 feet. A fragile wire network is erected and serves as part of the steel reinforcement which is left in position; the method consists of placing the steel fabric (triangular mesh weighing about 1.8 lb/ft^2, which is equivalent to a steel-plate thickness of 0.043 inch) to the required shell diameter. Reinforcing bars about 0.25 inch in diameter are laid on both sides of this network and wired to the network; the bars take the slab stresses, particularly those due to concrete shrinkage. Below all this steel is erected a light scaffold (sometimes hung to the network) which in turn carries the light removable formwork. Shotcrete, having a compressive strength of 3,000 psi at age 28 days, is then applied to cover the reinforcement and protect it from the elements. The concreting is carried out concentrically from the springing to the crown of the shell. When the shotcrete is set, the rings of concrete are self-supporting, and the reinforcement supports only the weight of the unset rings. An accurately shaped structure allows the shell to be of minimum thickness, permits the use of a lightweight substructure, and obviates heavy scaffolding. In this connection the reader should also refer to the work of A. M. Haas (1962).

Expansion joints are always a problem and need careful designing. It is not always possible to put straight joints through a slab. According to Snow (1947), one knows that cracks will occur, and one must therefore try to control them so that they will develop where they are expected. In concrete-shell construction, it is more difficult to know where to put the expansion joints. Snow believes that intervals of 150 feet are too long and that the intervals of expansion joints should be kept down to 60 feet.

In 1923 the Berlin-Dahlem National Bureau of Materials Testing conducted tests (Schluter, 1923) on the behavior and bearing strength of thin-shell Gunite continuous roofing. Four 1-inch-thick wire-reinforced slabs, each 20 inches wide and 23 feet long, were made by spraying Gunite over steel fabric (ten or thirteen 0.12-inch-diameter wires interwoven with 0.20-inch-diameter rods spaced transversely at 1-inch intervals). Maximum size of aggregate was about 0.250 inch.

The C/A, by volume, was 1:5 in two slabs and 1:7 in the other two slabs. At ages between 63 and 77 days, each slab was mounted on five small columns so that the intervening spans were nearly 6 feet center to center. Concentrated loads were applied, deflections were measured, crack development was correlated with loading, and loading was continued until failure. It was observed that cracking on the slab's underside occurred much later than that on the upperside above the column supports — specifically, at 995 psi for slabs having a C/A of 1:5 and at 1,100 psi for those having a C/A of 1:7. The average flexural stress at failure was found to be 1,920 psi for slabs containing the 10-wire fabric arrangement and 2,530 psi for slabs containing the 13-wire fabric arrangement, regardless of C/A value. Deflections immediately prior to failure were as great as 1.6 inches. The average compressive strength, based on 1-inch test cubes sawed from the slabs, was 7,500 psi for a C/A of 1:5 and a minimum of 4,270 psi for those having a C/A of 1:7. Reinforced thin-shell shotcrete roof slabs represent a highly elastic sheathing that has many practical advantages. The second part of Schluter's paper is concerned with flat-slab roof construction for a warehouse in Berlin and contains varied data of interest to the structural engineer.

Wallace Neff (1964)*, Los Angeles, has advised me that the design criteria he uses for shotcreting his patented balloon forms, which have been described by Wiehle (1953b) are those he obtains from Richard R. Bradshaw, Van Nuys, California. Neff's design of the hotel erected recently in the Virgin Islands calls for a pneumatically applied coral concrete thin-shell structure. Four legs support the thin shell. Design factors were obtained from Bradshaw who specializes in structural design of thin-shell concrete structures. According to Bradshaw (1964)*, who is a member of the ASCE Task Committee on Limit Design (part of the ASCE Structural Division), his shotcrete structural designs are based on the assumed compressive strength (at age 28 days) which is specified in the contract. The thickness of the shell is dependent on this property alone. He pays no heed to factors such as coefficient of thermal expansion, bond resistance to pullout, drying shrinkage, or flexural strength, because his experience has disclosed that such data are unnecessary for thin-shell structural concrete design. Bradshaw believes that the nozzleman's judgment and technique are more important than a miscellany of design data. In Bradshaw's opinion, skill of the artisan is the secret to successful shotcrete.

Since the close of World War II, many prefabricated Gunite houses have been built in India (Venkataram, 1950). The ultimate compressive strength of the Gunite is 6,000 psi, and the ultimate strength in shear and tension is 600 psi. The C/A values are 1:6 for wall slabs and 1:4 for columns, roof slabs, and floor slabs. All slabs are 2 inches thick, and the walls consist of double slabs. By 1952, the method had been developed in India to the point where three-story quarters were under construction (Venkataram, 1952). Reinforced shotcrete roof slabs 1 foot wide by 2 inches thick, and with spans up to 12 feet, were used.

*Private communication of 9 Nov. to W. R. Lorman.

Federal Housing Administration specifications require shotcrete (for walls in residential structures) to have a compressive strength of at least 3,000 psi at age 28 days (Anon., 1950).

Structural designers usually specify that wire-fabric reinforcement should have a minimum area in each direction equal to 0.0025 times the cross-sectional area of the shotcrete structural section (Anon., 1958).

Encasement in shotcrete (Anon., 1962b), discussed in the section herein entitled "General Facts About Shotcrete Construction" and in the subsection "Compressive, Flexural, and Tensile Strength," presumably enhances the resistance of the buildings (varying in height from 22 to 44 stories) to seismic and wind forces. Though no design allowance was made for the shotcrete in computing shear and bending capacity of the encased beams, the beam stiffness was increased from 20 to 60% (depending on the size of beam).

Cowan (1956) has shown how to compute stresses in the hardened shotcrete, applied either before or after a cylindrical prestressed-concrete storage tank is filled with liquid. His explanation considers creep and shrinkage of the shotcrete and shows how to allow for these factors mathematically.

In prestressed-concrete tanks designed and erected by the Preload Company, New York, New York, the floors have no expansion joints if shotcrete is used (Closner, 1958). Conventional concrete floors normally are subdivided into panels to expedite construction; thus, every construction joint eventually becomes an expansion joint that requires a rubber waterstop. The floor thickness for a 350,000-gallon tank is 4 inches if made of conventional concrete and 2 inches if made of shotcrete. In either case, 0.05% steel reinforcement in each direction is customary. Shotcrete walls are customary if the tank wall thickness is 6 inches or less, and conventional concrete is employed if the walls are thicker. Rubber waterstops are used in all vertical joints. After the exterior prestressed circumferential wires are in place, shotcrete is gunned over the wall exterior to bond the wires to the wall. An exterior coat not thicker than 0.75 inch supposedly provides sufficient protection against corrosion of the prestressed reinforcement.

Prestressed-concrete tank-wall construction by the National Gunite Corporation, Boston, Massachusetts, is based on a shotcrete designed compressive stress of 1,800 psi and on circumferential wire at a designed tensile stress of 140,000 psi. Instead of rubber waterstops at vertical joints, a continuous steel diaphragm is used throughout the wall. Shotcrete also is used in the 2-inch-thick 150-foot-diameter shell domes, as well as for the 2-inch-thick floors. According to Crowley (1958), the modern prestressed-concrete tank is considerably less expensive than early prestressed tanks. The amount of reinforcement required in the old-style prestressed-concrete tank, utilizing steel rods and turnbuckles, would be 11 times as much as in the modern wire-wound tank, and more than three times as much shotcrete would be required.

SHOTCRETE SPECIFICATIONS

One of the most up-to-date specifications for shotcrete is that issued by the AREA (Anon., 1964) in 1964. This specification applies to the use of shotcrete for repairing masonry and for protecting structural steel.

The fourth draft of the ACI Committee 506 Recommended Practice for Shotcrete (Reading et al, 1965) is another up-to-date reference that reflects current practice concerning shotcrete construction. This document provides for dry-mix and wet-mix processes and stipulates the various uses of shotcrete for structures; it gives information concerning proportioning and qualification testing of shotcrete, equipment requirements, qualifications and duties of the craftsmen, and various other requirements. Pending the adoption of the recommended practice (fourth draft version) recently prepared by ACI Committee 506, the official ACI standard for shotcrete is that appearing in ACI Standard 805-51.

Many specifications for fine shotcrete require that the mixture should have a cement - sand ratio of 1:3, by bulk volume, to be premixed dry before arrival at the gun. The term "dry" implies that the sand may contain moisture between practical limits of 4 to 8%. Sand with an average moisture content of 6% has a bulk about one-third greater than when oven-dry. Because of bulking, instead of 3.00 cubic feet in a 1:3 mixture, the amount is really 2.25 cubic feet of oven-dry sand. As the product is shot through the gun at high velocity, part of the sand bounces off the rigid surface and leaves mostly cement paste as the residue. Considering that rebound of the fine shotcrete is nearly all sand, the 2.25 cubic feet of oven-dry sand is reduced by 25%; stated otherwise, the shotcrete deposit contains 75% of 2.25 cubic feet of oven-dry sand; therefore, the cement - sand ratio of the deposit becomes 1:1.69 (by oven-dry volume) instead of the expected 1:3.00 (by bulk volume). In view of the variability of sand bulking, the specification for shotcrete should not require adherence to a specific percentage of moisture in the sand (assuming that mix proportions would be on a bulk volume basis). Instead, the contractor should be allowed to vary the proportions so that the deposited shotcrete will have the desired cement - sand ratio. This means that the specification could incorporate a sentence such as follows: The proportion of sand should be varied as necessary in accord with the extent that the bulk of sand at the job site exceeds the bulk of the same sand when oven-dry.

TEST SPECIMEN FABRICATION

The engineering properties of hardened shotcrete can vary significantly with the composition of the mixture, manner of premixing, and placement procedure. Satisfactory gunning and resultant quality can vary widely with the type of equipment used and the skill of the nozzleman. Factors other than mix proportions and premixing process are important in shotcrete work; such factors include weather, work-site conditions, scaffolding arrangement, nozzle diameter and pressure, distance of nozzle from the surface being sprayed, nozzleman's experience, and treatment of shotcrete after deposition.

Determining the average physical properties of hardened shotcrete depends on obtaining satisfactory test specimens; those that are sawed or drilled from small panels, made especially for test purposes and by experienced shotcrete operators, would seem to be the ideal specimens; those that exhibit discrepancies (e.g., laminations, segregation, voids, or any combination) would indicate incorrect gunning, improper mix proportions, or both.

Procedures for fabricating shotcrete test specimens have been described in the technical literature (Doull and Kline, 1947; USBR, 1951; Crom, 1951; Crom, 1964). However, there are differences of opinion relative to which method provides a truly representative specimen; this situation is probably why standard methods have not yet been established. The rebound problem would cast doubts on the reliability of test specimens made by gunning shotcrete into 6-inch-diameter cylindrical cages of hardware cloth mounted on a wooden board. Two-sided open-ended wooden molds (having open tops or exposed faces) appear most desirable as a means of fabricating test specimens in the shape of cubes and rectangular parallelepipeds. The plane of the open top during gunning would be vertical to simulate a structural wall, sloping to simulate an inclined structural surface, and horizontal to simulate a shotcrete floor. These approaches constitute one phase of the experimental program recommended later.

USBR laboratory studies (Vertrees et al, 1947) at Grand Coulee Dam showed that cylindrical test specimens (3 inches in diameter by 6 inches long) of shotcrete (C/A of 1:4, by volume) gunned horizontally, using Bondact equipment, display a better appearance and less sand streaks than do those gunned vertically downward. The use of 0.500-inch-square-mesh hardware cloth (as a cage mold) results in higher compressive strength, at age 28 days, than when 0.250-inch-square mesh is used.

Section 2605 of the Uniform Building Code (PCBO, 1949) requires that test cylinders of shotcrete be made in a manner that permits the air blast to compact the constituents and to escape without causing back pressure. Such test specimens must be made at the place where the concrete is being shot.

According to Linder (1963), the compressive strengths of test specimens extracted from the shotcrete structure are approximately equal regardless of whether the load is applied perpendicularly or parallel to the direction in which the layers have been gunned.

SUMMARY

Throughout the technical literature, there are many claims (some supported by experimental data) that shotcrete is stronger, denser, and more resistant to deterioration than conventional concrete. Whether or not shotcrete always possesses these attributes is a moot question, since its quality depends mainly on the nozzleman and the inspector.

Premixed-dry shotcrete has been in use since 1910 and often is referred to as Gunite. Premixed-wet shotcrete is a recent development, having been in use since 1955. Aggregate as large as 0.750 inch was first used in 1960.

The use of premixed-wet shotcrete offers the following advantages over premixed-dry shotcrete: (1) aggregates may be delivered to the mixer in any moist condition; (2) constant water-cement ratio is assured after correcting for the moisture content of aggregate; (3) the constituents are thoroughly mixed before transmission to the gun; and (4) the nozzleman need be concerned only with properly gunning the shotcrete into place.

Though the published technical data concerning physical properties of hardened shotcrete indicate a wide range in values, good hardened plain shotcrete is generally quite similar to hardened plain concrete or mortar having the same mix proportions and that has been fully compacted. The water-cement ratio (by weight) of shotcrete usually ranges from 0.31 to 0.53, which is equivalent, respectively, to 3.5 and 6.0 gallons per bag. The average shrinkage of shotcrete varies between 0.05 and 0.15%, whereas that for conventional concrete or mortar ranges between 0.05 and 0.08%. The ultimate creep of premixed-wet fine shotcrete is about seven times that of premixed-dry fine shotcrete, if the sustained compressive stress is 1,000 psi beginning at age 28 days. The average durability (i.e., resistance to failure caused by cyclic alternate freezing and thawing) of premixed-dry shotcrete (fine or coarse) is about twice that of premixed-wet shotcrete (fine or coarse). At age 28 days, compressive and flexural strengths may be as high as 13,000 and 1,400 psi respectively, tensile strength may be nearly 600 psi, and modulus of elasticity may range between 2.5×10^6 and 6.5×10^6 psi, all depending on shotcrete mix design and method of production. The strength of shotcrete is a function of the velocity at which ejection occurs, all other factors being equal. Shotcrete made with high-silica cement cracks less and creeps more than if it is made with either normal or high-early-strength portland cement. The average unit weight of hardened shotcrete made with common aggregate lies between 140 and 145 pcf. If shotcrete is correctly gunned into place, its bond to steel is greater than that of conventionally placed mortar or concrete. The coefficient of thermal expansion of premixed-dry fine shotcrete, incorporating common aggregate, is about the same as that of conventional concrete or mortar, lying between 5×10^{-6} and 7×10^{-6} in./in. per degree F. The average swellage, due to moisture gain, of premixed-dry fine shotcrete at age 1 week is about 2×10^{-4} in./in. The abrasion resistance of hardened premixed-dry

fine shotcrete is greater than that of hardened conventional concrete or mortar at comparable water-cement ratios. The permeability of hardened shotcrete appears to be of the same order of magnitude as that of fully compacted and properly cured conventional concrete.

RECOMMENDATIONS

An experimental program, the essentials of which are outlined here, could serve in developing additional information concerning the engineering properties of hardened shotcrete. The factual relations, among controlled physical factors and certain observable characteristics of shotcrete, could be useful in establishing structural design criteria for new construction and also for repairs to old structures.

The approach to this program should be as follows: Erect formwork for gunning wall panels of shotcrete, each reinforced with one sheet of steel-wire fabric. Certain areas of each wall panel should be devoid of reinforcement to assure extraction of plain shotcrete test specimens. Alongside each wall panel, erect a rack for supporting a panel of open-ended molds which, after being gunned, are the source of small plain shotcrete test specimens.

Prismatic test specimens of plain shotcrete for rupture modulus tests should be sawed from each of four wall panels. Large cubical test specimens (each containing one steel reinforcing bar) for bond pullout resistance tests and large cubical test specimens of plain shotcrete for compressive strength tests should be sawed from each of the remaining four wall panels. Small cubes and small right prisms should be removed from each rack panel.

The physical characteristics to be investigated should be the following: Young's modulus of elasticity (dynamic), unit weight, flexural strength, compressive strength, and bond resistance to pullout of embedded steel. Specimens from all panels should be tested at age 7, 14, and 28 days. All panels should be moist-cured at the work site until at least age 7 days before extraction or removal of the test specimens. Storage of all test specimens should be in 73°F fog until the time of test.

The mixtures to be investigated should involve two designs, one containing 0.750-inch and one containing 0.375-inch maximum-size aggregate. Coarse and fine aggregates should be combined to assure gradation in accordance with the current revision of ASTM Specification C33.* Cement content should be at least six bags per cubic yard of premixed-wet concrete; cement-aggregate ratio, 1:4 (by weight); water-cement ratio, 0.4 (by weight); and slump, 1 inch or less. These values should be in effect at the time the freshly mixed concrete is discharged from the mixer and before it enters the shotcrete system.

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*See references.

After analysis and interpretation of the experiment, certain factual data would indicate whether or not the use of coarse shotcrete (0.750-inch maximum-size aggregate) is preferable to fine shotcrete (0.375-inch maximum-size aggregate). The resultant correlations would pertain to density, elasticity, and strength (bond, compressive, and flexural) of only premixed-wet shotcrete. The experimental data would also serve in establishing information concerning shotcrete-test-specimen fabrication at the site of construction; the facts would show whether or not comparatively small test specimens, made by gunning prismatic open-ended wooden forms, truly exemplify the engineering properties of hardened structural shotcrete.

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The important technical information gleaned from a literature survey covering the past 55 years of laboratory and field experiences with mortars and concretes applied pneumatically (i.e., shotcrete) is presented. In addition to general facts concerning this method of construction, various physical properties of hardened shotcrete, which have been investigated by numerous researchers, are discussed. Insofar as strength and elasticity are concerned, hardened shotcrete generally is quite similar to hardened mortar or concrete made in the conventional manner and fully compacted. An experimental program is recommended for (1) developing supplementary data with regard to density, elasticity, and strength (bond, compressive, and flexural) of hardened shotcretes (premixed wet) made with 3/4-inch as well as 3/8-inch maximum-size aggregate, and (2) ascertaining whether or not comparatively small prismatic test specimens truly represent the engineering properties of hardened shotcrete in large wall panels.

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