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SHOTCRETE FOR EXPEDIENT STRUCTURAL REPAIR

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13. ABSTRACT (Maximum 200 words) Shotcrete, or pneumatically applied concrete, is presented as a method for expedient repair of structures in a postattack environment. A brief history of shotcrete is presented, along with a description of the two main processes, dry-mix and wet-mix. Engineering properties of shotcrete are discussed, along with methods for evaluating those properties. Special shotcrete mixtures are discussed, and fibrous shotcrete is presented a good material for structural repair because of its combination of high flexural strength and ductility. Automated shotcrete equipment is discussed and a concept for a Mobile Automated Shotcrete Expedient Repair Vehicle (MASERV) is presented. Specific recommendations are made for a proposed field test, as well as general recommendations for future research on shotcrete.				
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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this report is to document a literature review of shotcrete as a candidate technology. This effort supports a bigger project, to identify, test, evaluate, recommend, and develop construction materials, equipment, techniques, and training for expedient repair of conventional weapons damage to structures in PACAF and USAFE in a postattack environment.

B. BACKGROUND

Expedient repair of critical structures is a major concern for the Air Force, because both the Pacific Air Force (PACAF) and United States Air Force Europe (USAFE) missions depend on base recovery capability. In a postattack environment, both personnel and equipment must be protected from damage suffered during the attack and from subsequent attack(s). With this in mind, two major goals of expedient repair for structures emerge, structural repair and sealing protection. Expedient repair for structural rehabilitation should recover sufficient structural capability to stabilize the structure and minimize the propagation of damage. Sealing protection is a less obvious, but equally important reason for expedient repairs in the postattack environment. Simple weather conditions, such as rainfall, could be a threat to some mission-critical equipment. Other, more severe, weather conditions could also threaten mission-critical personnel. In addition, chemical and/or biological intrusion, either by accident or by design, cannot be ruled out as a threat in the postattack environment. Shotcrete is an attractive alternative, because it can meet both of the goals of expedient repair simultaneously.

C. SCOPE

The report includes a general description of shotcrete, including terminology, equipment, material properties, and methods of mixing and placing, with an emphasis on the use of shotcrete for expedient repair. Training of personnel for shotcrete utilization is discussed and a plan for

training is presented. Special shotcrete mixes (such as fibrous shotcrete) are discussed. Specialized shotcrete equipment is discussed and a concept for a Mobile Automated Shotcrete Expedient Repair Vehicle (MASERV) is presented. Recommendations are made for field evaluation of shotcrete for the expedient repair of structures and for possible research on the use of shotcrete.

D. METHODOLOGY

Shotcrete is a general term for mortar or concrete pneumatically projected, or gunned, at high velocity onto a surface. Although conventional concrete can be molded into any shape by placement in a form, shotcrete has the added advantage of using only a backup surface as a light form, or even no form. In new construction, shotcrete is well adapted for thin, lightly reinforced sections. The major advantages of shotcrete are the convenience of application and the high degree of bonding which can be achieved. Shotcrete has similar properties to cast-in-place concrete formed at the same water/cement ratio and density. However, the density of shotcrete *in situ* tends to be higher than cast-in-place concrete of similar design, particularly when placed by the dry-mix process. Also, the void content and permeability of shotcrete are lower than for cast-in-place concrete of similar design. Shotcrete is very durable when subjected to severe freeze-thaw conditions, the opposite of the expected behavior for a concrete with low void content. This phenomenon has been attributed to the low permeability which provides sealing.

The two common processes of producing and placing shotcrete, the dry-mix process and the wet-mix process, differ primarily in the way mix water is added. In the dry-mix process most (or all) of the mix water is added to the mixture by a water ring (or rings) at or near the nozzle. In the wet-mix process, the mixture is produced in a batch, with mix water added before transporting the shotcrete material. The dry-mix process has the advantage of scheduling flexibility. Dry-mix process shotcrete use can be suspended almost instantaneously, because hydration does not begin until the mix reaches the nozzle. In addition, a strong selling point for the dry-mix process is the success this process has with accelerating admixtures. With the addition of accelerators, it is possible to achieve very high early strengths. The dry-mix process is also the method which has achieved the highest ultimate strengths. However, high early strength and high ultimate strength appear to

be mutually exclusive, and care must be used when designing the mix to insure that all strength requirements are met. The major disadvantage of the dry-mix process is the need for an experienced crew. Wet-mix shotcrete can be delivered with much more uniform properties and at much higher production rates, but typically is delivered at a lower velocity, which leads to lower *in situ* density, and, in turn, lower *in situ* strength.

Special shotcrete mixtures include regulated-set cement shotcrete, latex shotcrete, polymer shotcrete, and fibrous shotcrete. The first three types share two major disadvantages for expedient repair: difficulty in long-term storage, and difficulty in intermittent use. However, fibrous (steel-fiber-reinforced) shotcrete has great potential for expedient repair purposes. Numerous examples of the successful use of fibrous shotcrete mixtures for structural rehabilitation can be found in the literature. The addition of fibers to shotcrete improves material properties including ductility, toughness, flexural strength, impact resistance, fatigue resistance, and compressive strength. Although other fiber types are available, steel fibers are most commonly used. Existing equipment with little or no modifications can be used for the application of steel-fiber shotcrete, when special fibers are used. These have deformed ends and are glued together to reduce balling. In addition, specialized equipment is available for the addition of fibers and the application of fibrous shotcrete.

The use of automation in the shotcrete process has numerous advantages. The two most important advantages of automated shotcrete equipment are: (1) the nozzle operator can be relieved of much of the repetitive functioning typically associated with shotcrete application, allowing maximum concentration on delivering top-quality shotcrete, and (2) measures to improve safety in hazardous situations can be easily implemented. The most common use of automation has been in tunnel linings, but general-purpose automated shotcrete equipment is also commercially available.

E. RESULTS

A concept was developed by the author of an advanced repair vehicle called MASERV (Mobile Automated Shotcrete Expedient Repair Vehicle). The MASERV concept includes all of the automated functions of commercially available robotic shotcrete machines, with some additional advanced features.

The MASERV is track-mounted and armored for use in a postattack environment. It can carry large volumes of materials and has a highly versatile robot arm attached to a cab which can be hydraulically lifted to allow repairs on upper floors of structures. While the MASERV concept is more advanced than the equipment currently available, some version of this vehicle (with many of the capabilities shown) could probably be built almost immediately if funding were available.

F. CONCLUSIONS

Shotcrete is a material which appears ideal for expedient structural repair. A primary advantage is the potential for use of locally available materials commonly used for Portland cement concrete, rather than having a stockpile of material earmarked for expedient repair. In general, shotcrete can provide rapid repairs for structural and sealing protection in a postattack environment. Automated equipment is available which allows shotcrete to be used in remote areas. Shotcrete, particularly when used with steel fibers, is very resistant to tensile/flexural failure and penetration, and it can be used as an expedient replacement for any proposed (cast-in-place) conventional concrete repair.

G. RECOMMENDATIONS FOR FUTURE RESEARCH

There are various needs for future research in the use of shotcrete for expedient repairs. Recommended research may be grouped into four general categories: materials research, research on methods of application, automated equipment research and development, and research on capabilities of personnel (including training methods). The MASERV (Mobile Automated Shotcrete Expedient Repair Vehicle) concept is achievable with an adequate research and development effort.

PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), under a Scientific and Engineering Technical Assistance (SETA) contract (F08635-88-C-0067) for the Air Force Engineering and Services Center (AFESC), Engineering and Services Laboratory, Tyndall Air Force Base, Florida. The work documented was performed at Tyndall Air Force Base, Florida, between 1 May 1989 and 31 November 1989. Capt Richard A. Reid, HQ AFESC/RDCS, was the project officer.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The overall objective of this effort is to identify, test, evaluate, recommend, and develop construction materials, equipment, techniques, and training for the expedient repair of conventional weapons damage to structures in PACAF and USAFE in a postattack environment. The objective of this report is to document a literature review of shotcrete as a candidate technology.

B. BACKGROUND

Expedient repair of critical structures is a major concern for the Air Force, because both the Pacific Air Force (PACAF) and United States Air Force Europe (USAFE) missions depend on base recovery capability. In a postattack environment, both personnel and equipment must be protected from damage suffered during the attack and from subsequent attack(s). With this in mind, there are two major goals of expedient repair for these structures, structural protection and sealing protection. Structural protection (rehabilitation) is the most obvious reason for expedient repair. If expedient repair is to be considered as a strategy, the damaged structure must retain at least some of its structural integrity. However, structural damage can lead to large deformations in structural members, damage propagation (e.g., cracking), and stress concentrations, which threaten personnel and equipment, and could even lead to catastrophic failure. Expedient repair for structural rehabilitation should recover sufficient structural capability to stabilize the structure and minimize the propagation of damage, so that there is a minimum risk to the mission in the postattack environment. Sealing protection is a less obvious, but equally important reason for expedient repairs in the postattack environment. Simple weather conditions, such as rainfall, could be a threat to some mission-critical equipment. Other, more severe, weather conditions could also threaten mission-critical personnel. In addition, chemical and/or

biological intrusion, either by accident or by design, cannot be ruled out as a threat in the postattack environment.

Because there are two distinct goals of expedient repair to structures in the postattack environment, it would be advantageous to utilize a method which could meet both goals simultaneously. Shotcrete, or pneumatically applied mortar/concrete, has this potential and has been the subject of an extensive literature review which is summarized herein.

C. SCOPE

This report includes a general description of shotcrete, including terminology, equipment, material properties, and methods of mixing and placing, with an emphasis on the use of shotcrete for expedient repair. Training of personnel for shotcrete utilization is discussed and a plan for training is presented. Special shotcrete mixes (such as fiber-reinforced shotcrete) are discussed. Specialized shotcrete equipment is discussed and a concept for a Mobile Automated Shotcrete Expedient Repair Vehicle (MASERV) is presented. Recommendations are made for field evaluation of shotcrete for the expedient repair of structures and for possible research on the use of shotcrete.

SECTION II

SHOTCRETE AS A CONSTRUCTION MATERIAL

A. HISTORY

Shotcrete is a general term for mortar or concrete pneumatically projected, or gunned, at high velocity onto a surface. Shotcrete was introduced in the early 1900s, under the trade name Gunit (Reference 1). Several proprietary names have been used for various mixtures which have been grouped under the general heading of shotcrete. The term, shotcrete, was first coined by the American Railway Engineering Association in the early 1930s and was adopted in 1951 by the American Concrete Institute to describe the dry-mix process. Shotcrete is now the accepted term for both wet-mix and dry-mix processes (Reference 2).

Conventional concrete can be molded into any shape by placement in a form. Shotcrete has the added advantage of using only a backup surface as a light form, or even no form. For example, shotcrete may be shot against the softest type of insulation material without serious damage to or compaction of the soft material (Reference 3). In new construction, shotcrete is well adapted for thin, lightly reinforced sections. Common uses include roofs, walls, canal linings, tunnel linings, swimming pools, prestressed tanks, thin overlays over structural materials, repair of concrete deteriorated by fire or earthquake, rock slope stabilization, and refractory linings for fireproofing. Shotcrete has properties similar to conventional concrete with the same mix proportions (Reference 2). The major advantages of shotcrete are the convenience of application and the high degree of bonding which can be achieved. The approximate cost of shotcrete is \$60 to \$150 per cubic yard (Reference 4). Shotcrete is generally economical, compared to conventional concrete, for layer thicknesses greater than 3 inches (Reference 4).

The use of shotcrete has been, and still is, controversial (Reference 5). Authorities who favor the use of shotcrete tend to oversell, promising unrealistic performance and engineering properties, while other authorities dispute any successful application of shotcrete. The real problem with shotcrete is that research conclusions, both in the laboratory and in

field observations of performance, have often been based on poor scientific techniques and on the researcher's prejudices (Reference 5).

B. SHOTCRETE PROCESSES

The two common processes of producing and placing shotcrete are known as the dry-mix process (Reference 6) and the wet-mix process (Reference 7). The two shotcrete processes differ primarily in the way mix water is added. In the dry-mix process most (or all) of the mix water is added to the mixture by a water ring (or rings) at or near the nozzle. Transport of dry-mix process shotcrete is done pneumatically, with the dry particles suspended by compressed air. In the wet-mix process, the mixture is produced in a batch, with mix water added before transporting the shotcrete material. Wet-mix process shotcrete can be transported by two methods, pneumatic feed and pumping. Pneumatic feed of wet-mix process shotcrete involves the transportation of "slugs" of wet mix by compressed air. Pumping of wet-mix shotcrete is accomplished by either a positive displacement pump or by a squeeze pump. In both methods, the wet-mix shotcrete is delivered by mechanical means in a semisolid state. When pumping is used, compressed air must be introduced at the nozzle to increase particle velocity during application. The methods of shotcrete transportation are illustrated in subsequent sections.

1. Dry-Mix Process Shotcrete

a. General

There is a standard pattern for most dry-mix shotcrete operations. First, the materials must be batched, usually in quantities of about 94 pounds of cement to 400 pounds of sand. The mixed material is carried in suspension by air to the nozzle. Water is injected at the nozzle and mixing is completed at impact. A sand heater is needed if the sand is very wet and is also useful in very cold climates. Types I, II, and III cements have been used, with Type I most common. Accelerating admixtures are often used in dry-mix shotcrete applications. A normal shotcrete sand has a fineness modulus of about 2.5, but special aggregates may be used. In addition, equipment is available to

gun shotcrete with larger aggregate (up to 1 inch diameter), but there are disadvantages, particularly the increased amount of rebound material.

b. Equipment

The minimum equipment for a dry-mix process shotcrete operation is the gun, an air compressor, material hose, air and water hoses, nozzle, and a water pump (if needed). The minimum operating air pressure is about 40 psi, but it is not uncommon to require about 100 psi to account for long hoses (greater than 100 feet) and increases in elevation (greater than 25 feet).

There are two main types of dry-mix process shotcrete guns, chamber guns and rotary guns. Figures 1 and 2 show a pictorial drawing and cutaway view, respectively, of a typical shotcrete chamber gun. The gun shown in Figures 1 and 2 is a double-chamber gun which has the advantage of delivering a continuous feed of material. The double-chamber gun works in two stages. In the first stage, the lower chamber is pressurized and the upper chamber is allowed to fill. In the second stage, the upper chamber is pressurized to force open the valve between chambers, allowing the material in the upper chamber to fall into the lower chamber. During both stages, the material in the lower chamber is kept under a positive pressure to ensure continuous feeding through the material hose. Figures 3 and 4 show cutaway views of two different types of single chamber, or batch, guns. Batch guns provide an intermittent feed since the chamber must be opened, depressurized, and then pressurized after the addition of a new batch of material. The batch guns shown in Figures 3 and 4 differ primarily in the method of feeding the material to the material hose, using a rotating agitator and a feed wheel, respectively. Batch guns have the advantage of simplicity, but have fallen into disfavor because of improvements in continuous feed guns. Rotary shotcrete guns, like the double-chamber gun, are capable of a continuous feed of material. Figures 5 and 6 show a pictorial drawing and a cutaway view of a rotary barrel gun. Figures 7 and 8 show a pictorial drawing and a cutaway view of a rotary-feed-bowl gun. The two types of rotary gun are similar, except for the method of delivering material to the outlet hoses. The rotary barrel gun discharges material from a series of rotating cylinders, which are filled on one side of the gun and discharged on the other side through a material hose (see Figure 6). The rotary-feed-bowl gun uses a gravity feed to

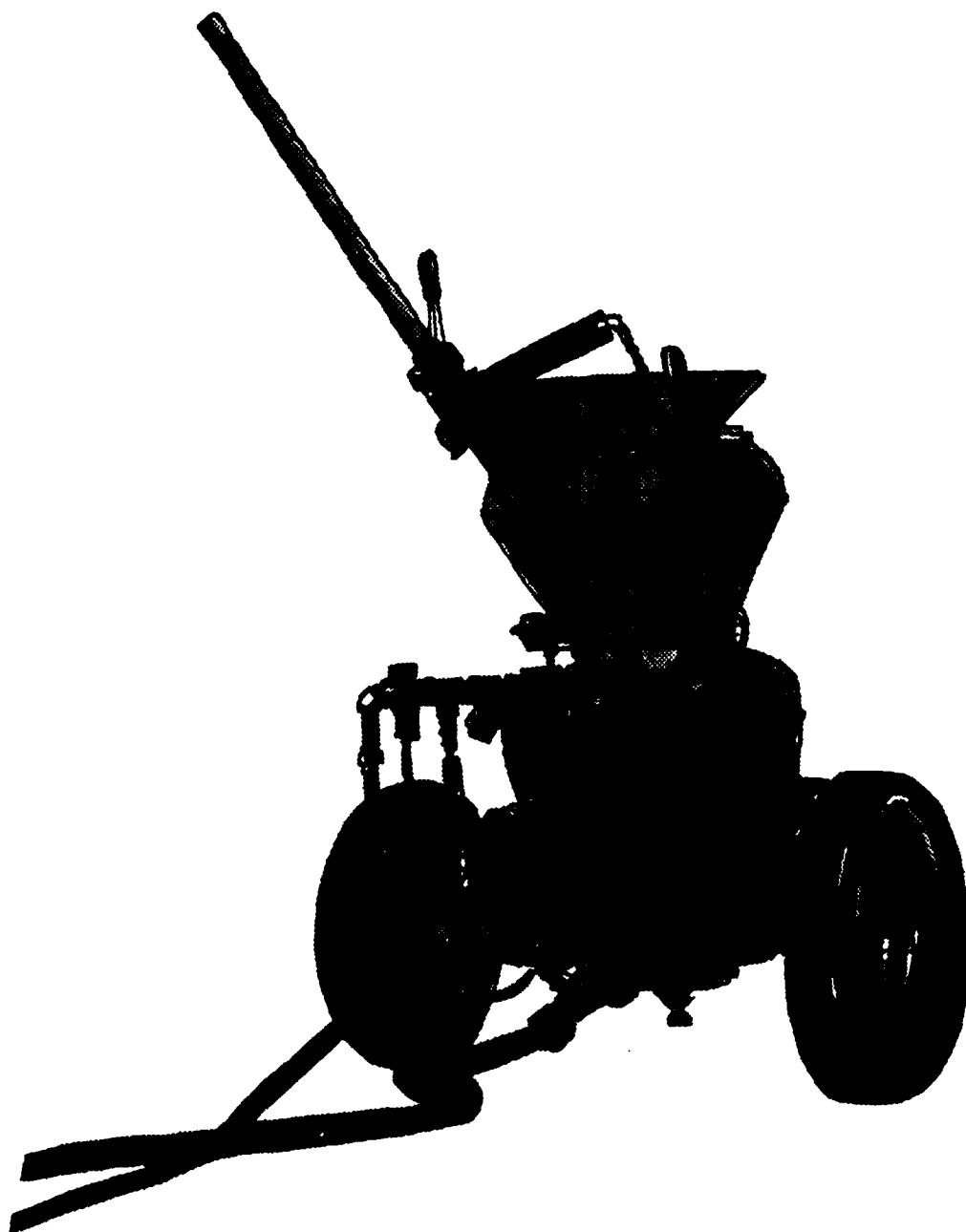


Figure 1. Pictorial Drawing of Double-chamber Gun.

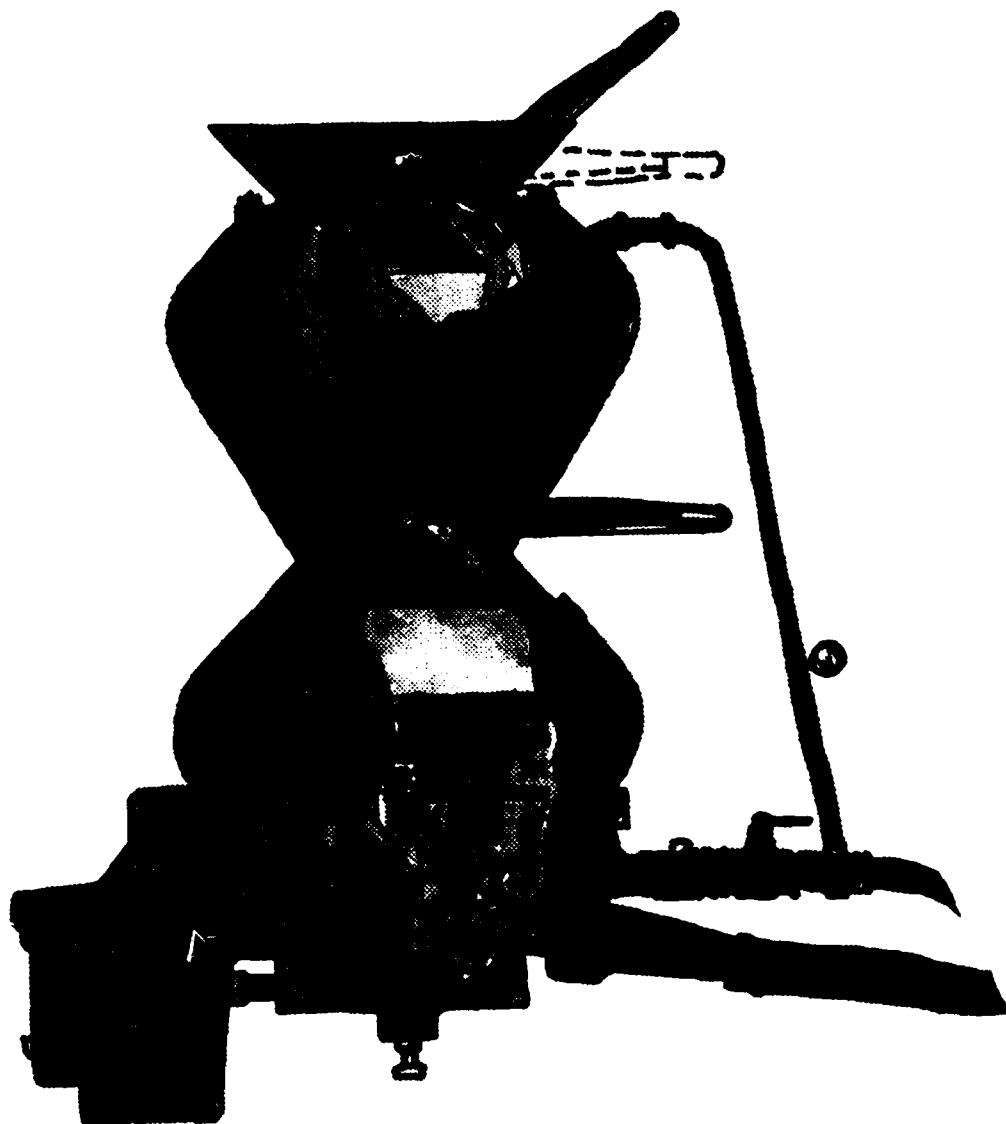


Figure 2. Cutaway View of Double-chamber Gun.

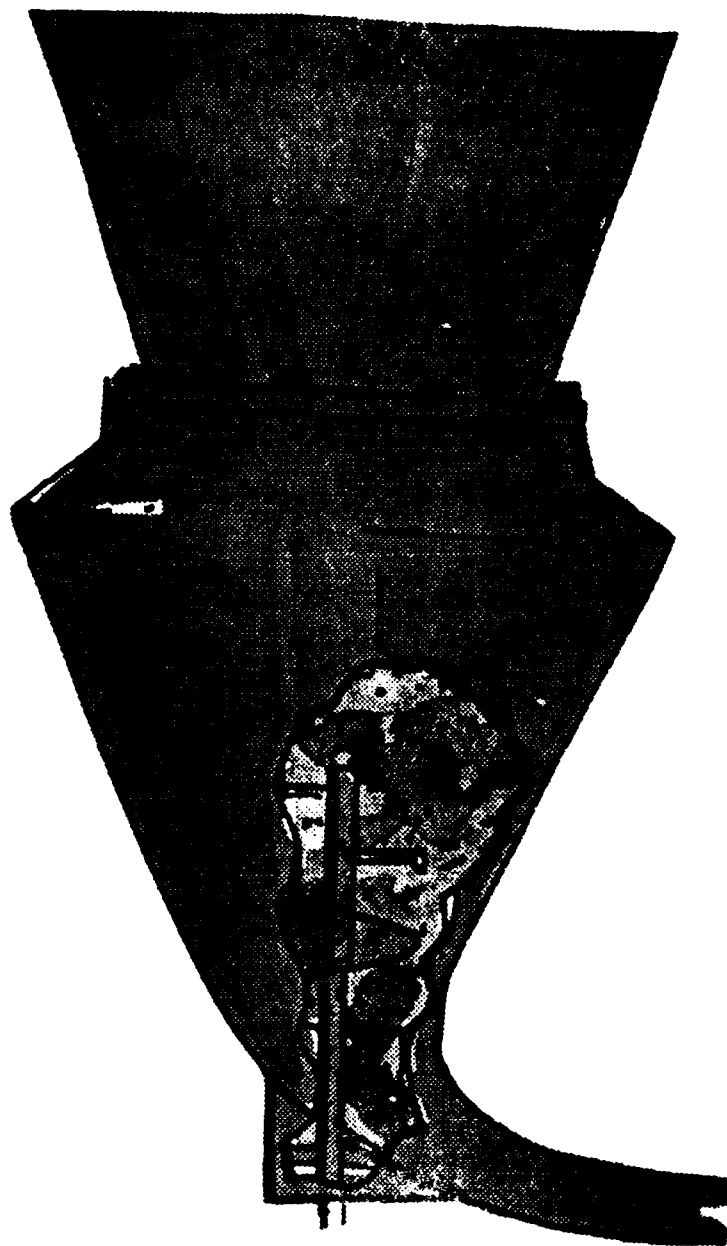


Figure 3. Cutaway View of Single-chamber Gun with Rotating Agitator.

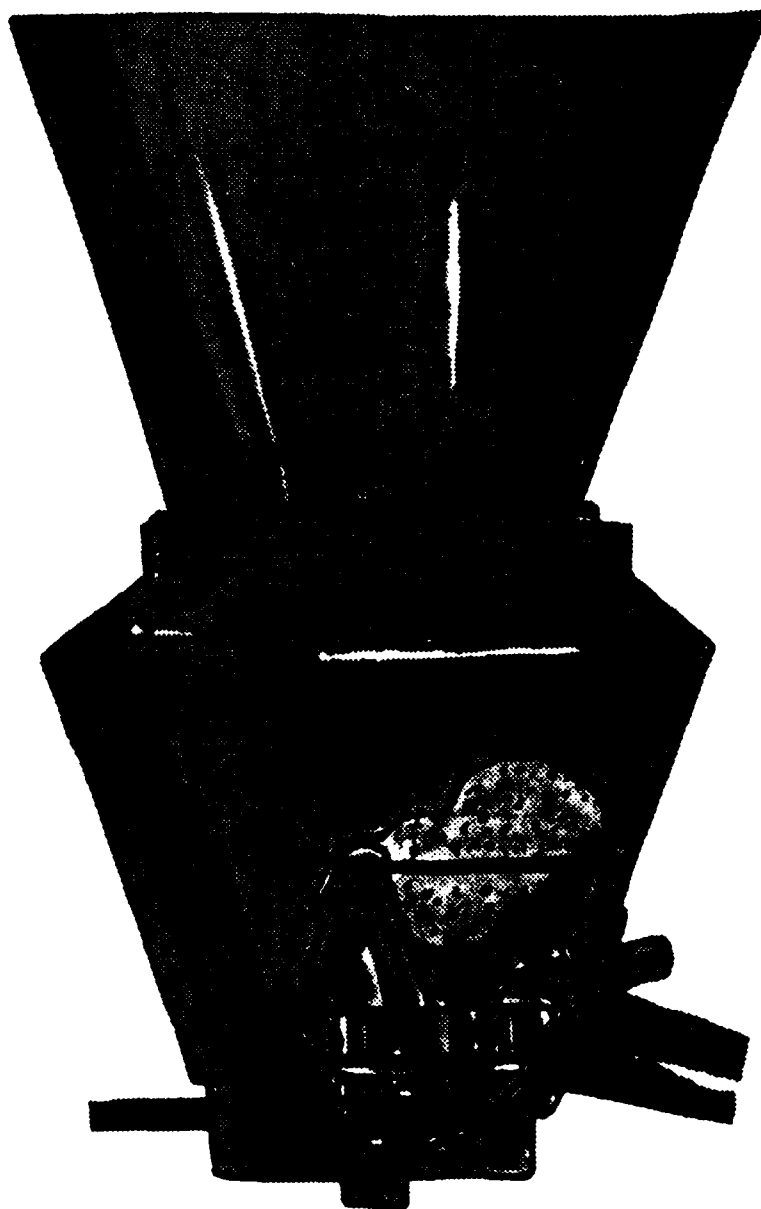


Figure 4. Cutaway View of Single-chamber Gun with Feed Wheel.

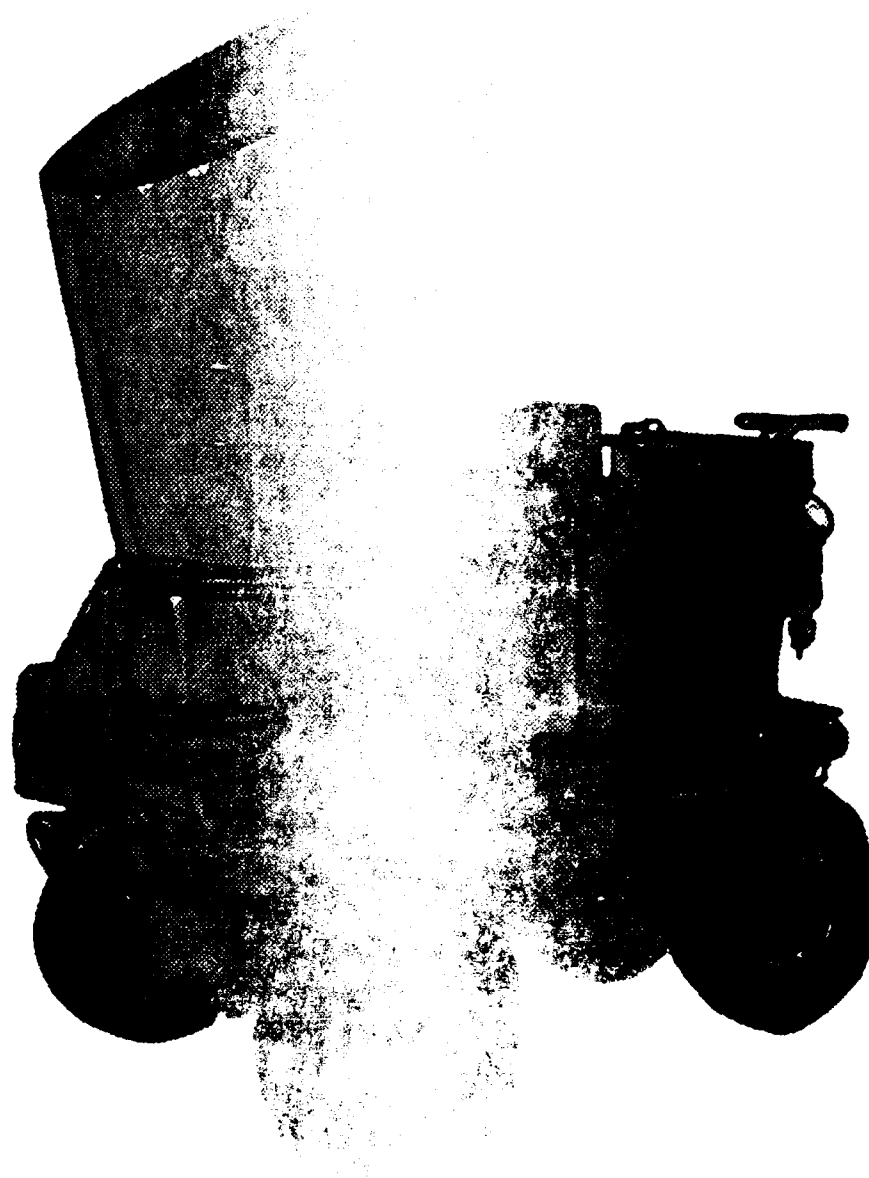


Figure 5. *Small, light-weight, rotary-barrel Gun.*

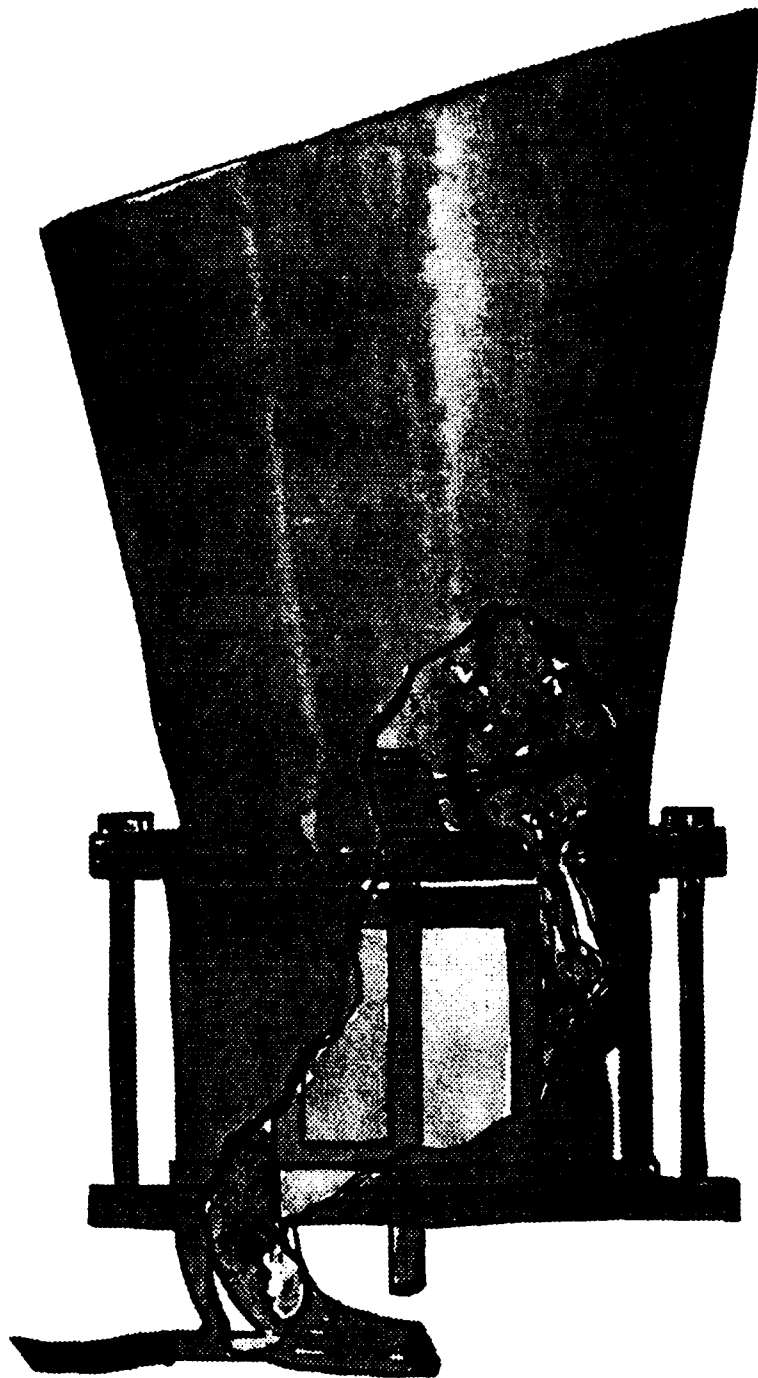


Figure 6. Cutaway View of Rotary-barrel Gun.

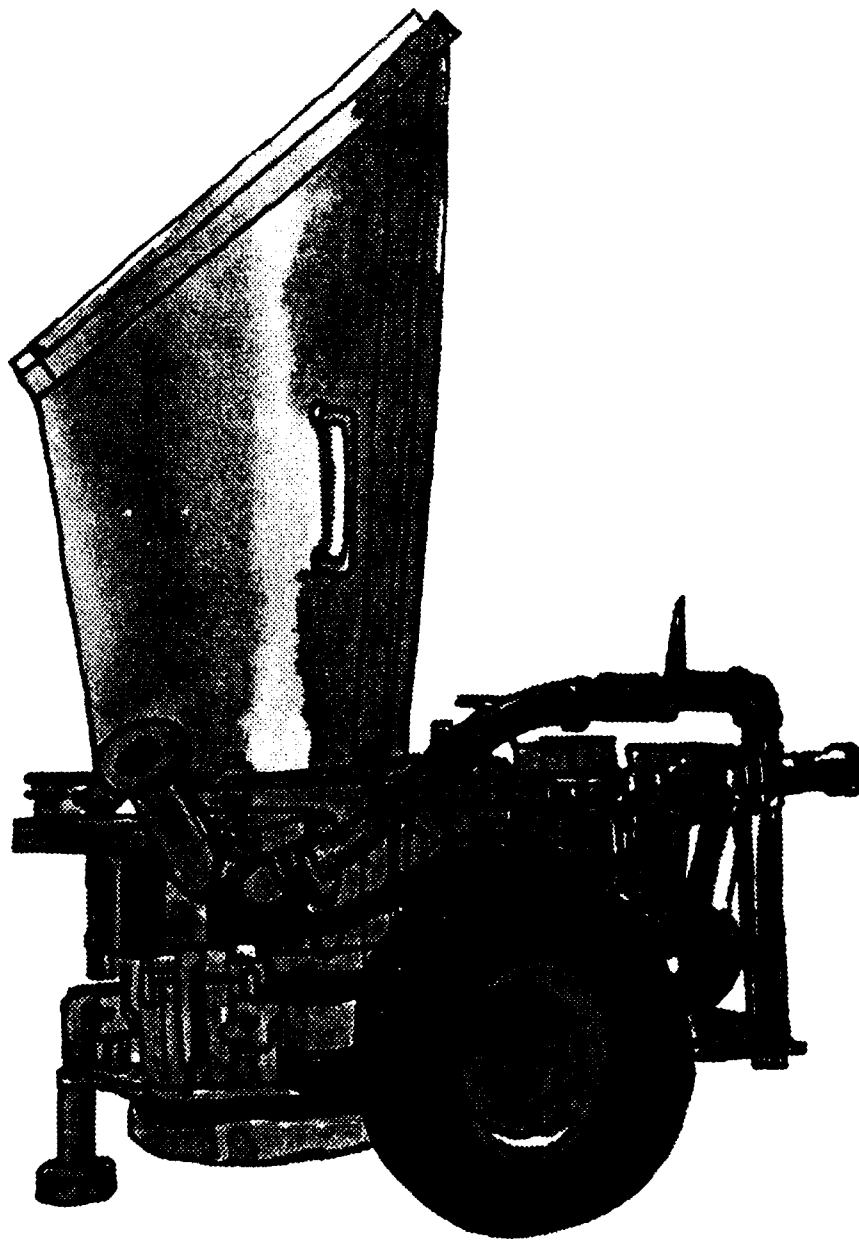


Figure 7. Pictorial Drawing of Rotary-feed-bowl Gun.

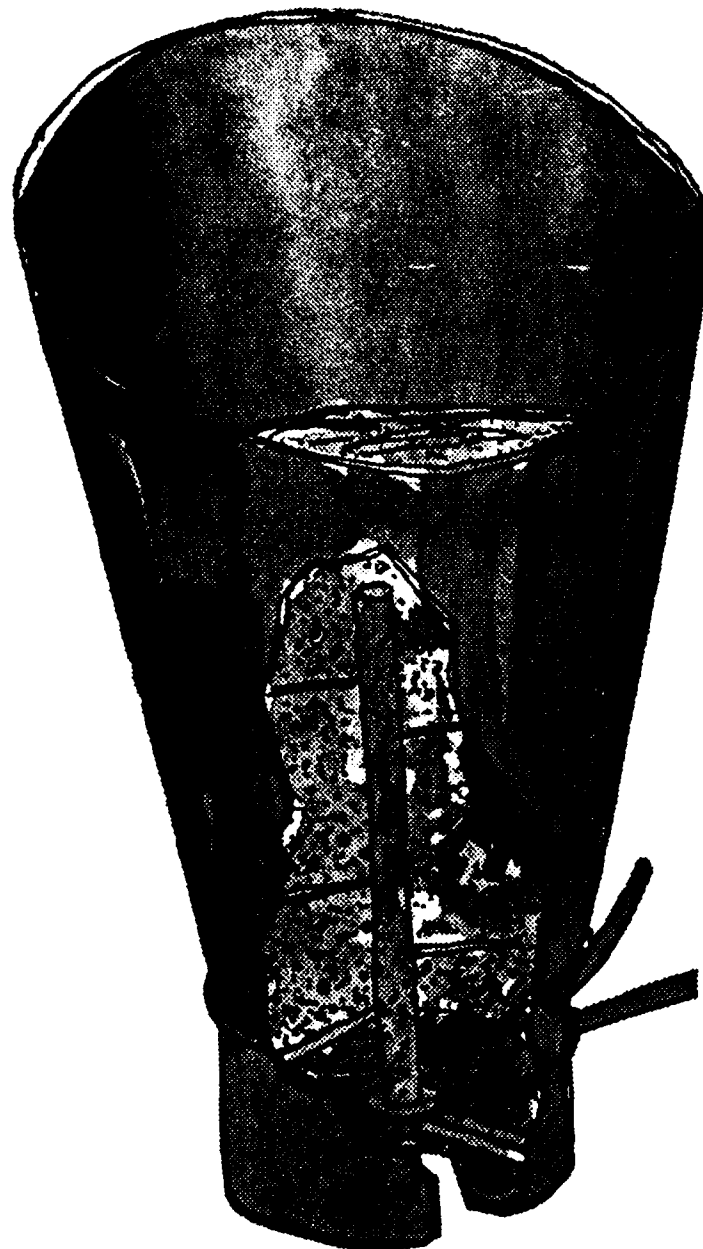


Figure 8. Cutaway View of Rotary-feed-bowl Gun.

fill the recesses in the feed-bowl, and the material is forced from the feed-bowl pneumatically (see Figure 8).

Figure 9 shows a cutaway view of a single venturi-type nozzle, which is typical for dry-mix shotcrete. The cutaway of the material hose shows the pneumatic delivery of the dry-mix. Other dry-mix nozzles include double venturi nozzles, tapered nozzles, and rifled nozzles. Nozzles usually connect along the axis of the material hose, but may have a 90-degree bend for some work. Figures 10 and 11 show two special types of nozzles, the premixing "hydromix" nozzle and the prewetting "long" nozzle, respectively. The hydromix nozzle (Figure 10) may be up to about 3 feet long and induces a premixing of dry-mix and water. The premixing nozzle is useful in reducing dust and particle rebound. The long nozzle (Figure 11) may be as long as 20 feet and is a relatively new type. The longer time for prewetting of the dry-mix can reduce rebound and may improve the quality of the *in situ* shotcrete.

Accelerating admixtures may be added using accelerator dispensers. Figure 12 shows a pictorial drawing of a typical auger-type dry-powder dispenser. The auger is calibrated to the gear train of the shotcrete gun. A cutaway view of the assembled dry-powder dispenser system is shown in Figure 13. Figure 14 shows a system for introducing liquid accelerators into the mix water before injection of water at the nozzle.

c. Advantages and disadvantages of the dry-mix process

The major advantages of dry-mix process shotcrete are: (1) flexibility, (2) little or no waste material, (3) high early strengths, and (4) highest ultimate strengths. Because dry-mix process shotcrete does not begin hydration until it reaches the nozzle, its use can be suspended almost instantaneously. This gives the operator a great amount of flexibility in scheduling. An experienced dry-mix process shotcrete crew can "jump" from one area to another with only a small loss in productivity. Similarly, this flexibility minimizes waste material. Since only the material needed is mixed, there is no need for the wasting of unused, but hydrated, shotcrete. One of the strongest selling points for the dry-mix process is the success this process has with accelerating admixtures. With the addition of accelerators, it is possible to achieve very high early strengths (typical

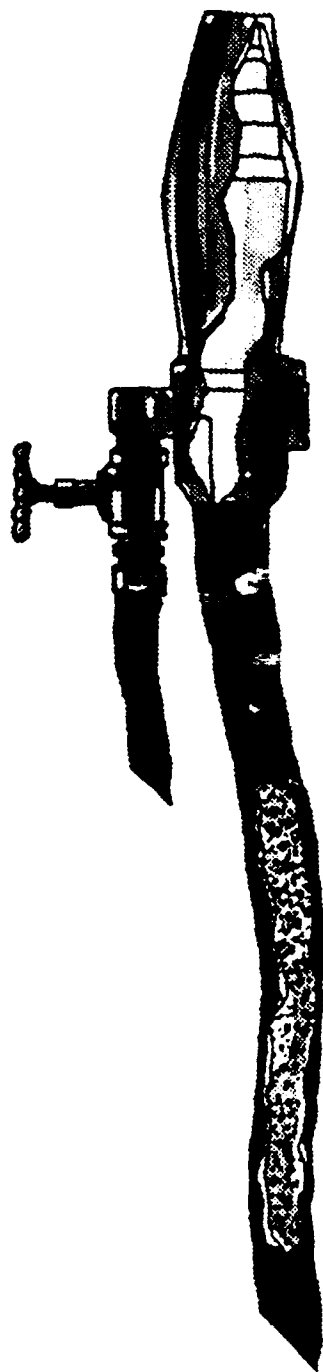


Figure 9. Cutaway View of Single Venturi Nozzle with Water Ring.



Figure 10. Pictorial Drawing of Premixing "Hydromix" Nozzle.



Figure 11. Pictorial Drawing of Prewetting "Long" Nozzle.

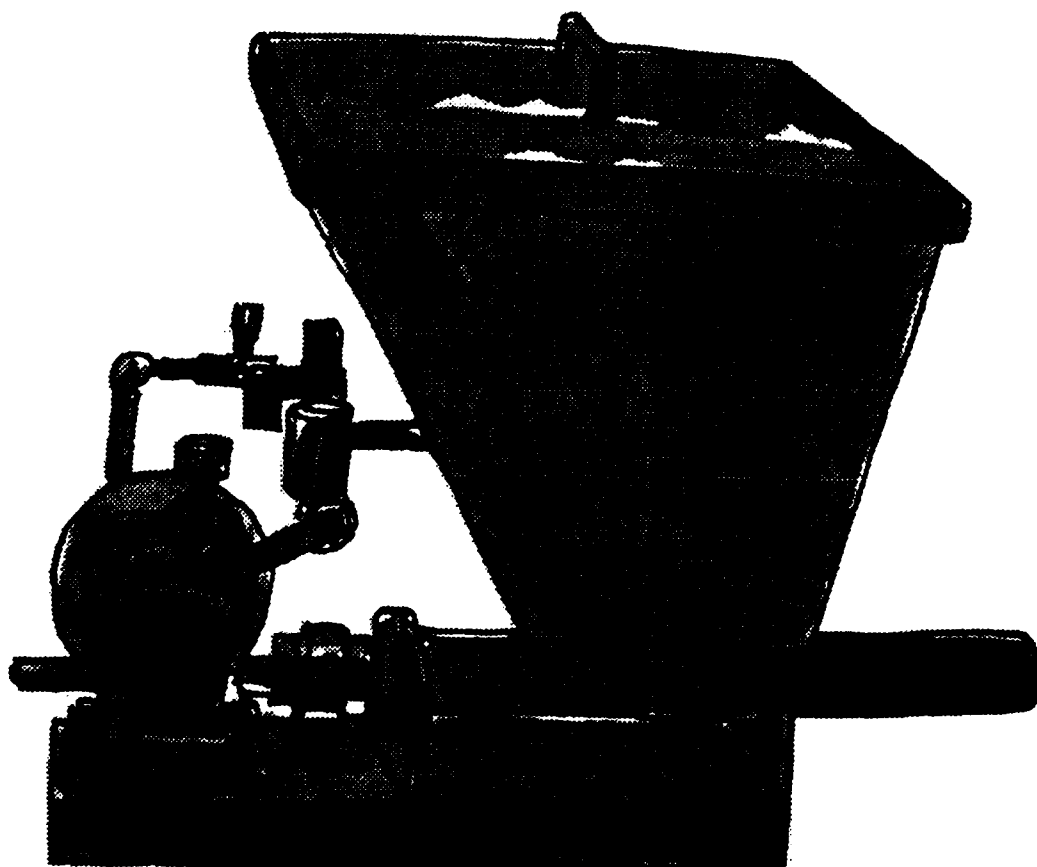


Figure 12. Pictorial Drawing of Dry Powder Accelerator Dispenser.

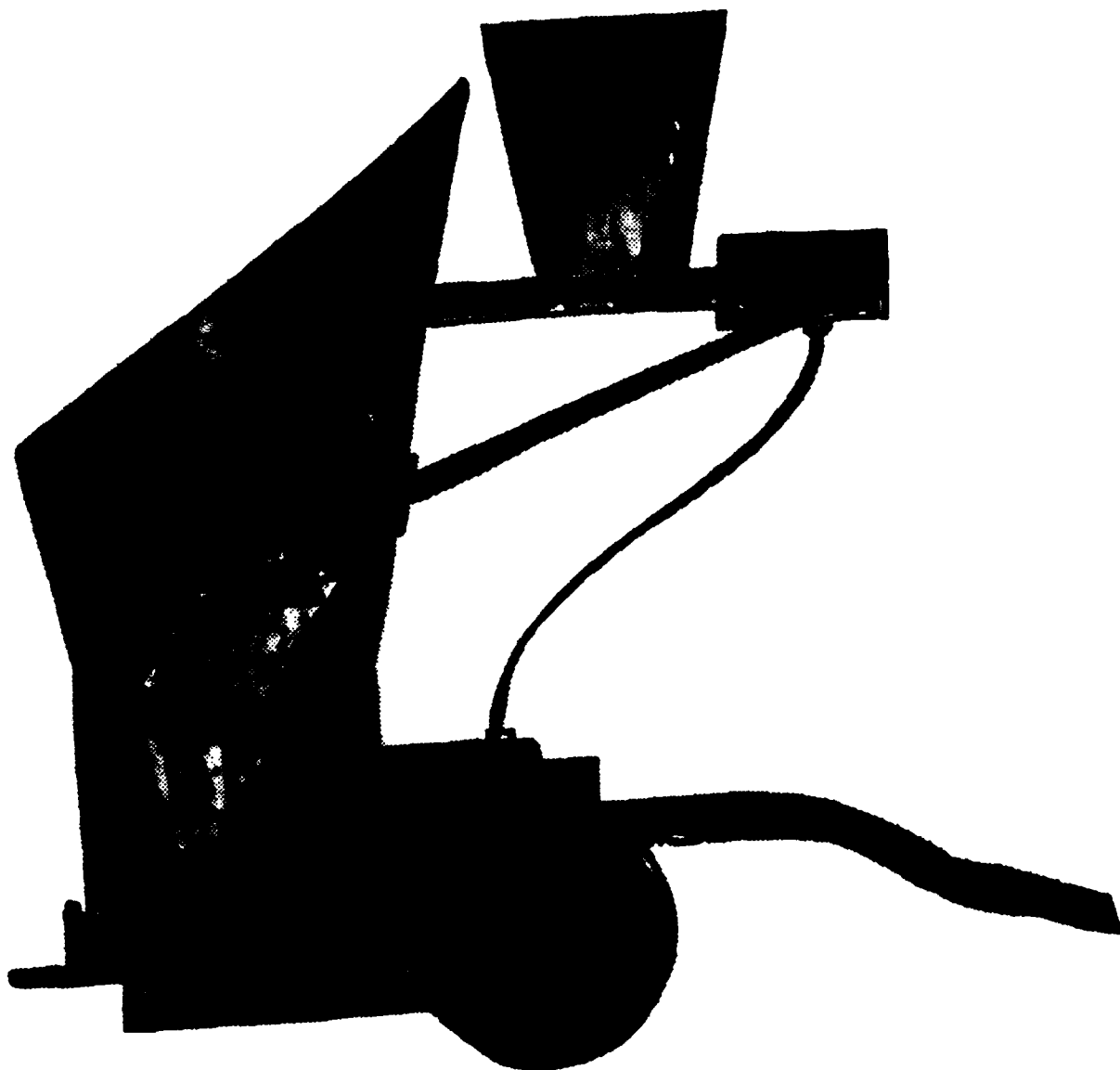


Figure 13. Cutaway View of Dry Powder Accelerator Dispenser System.

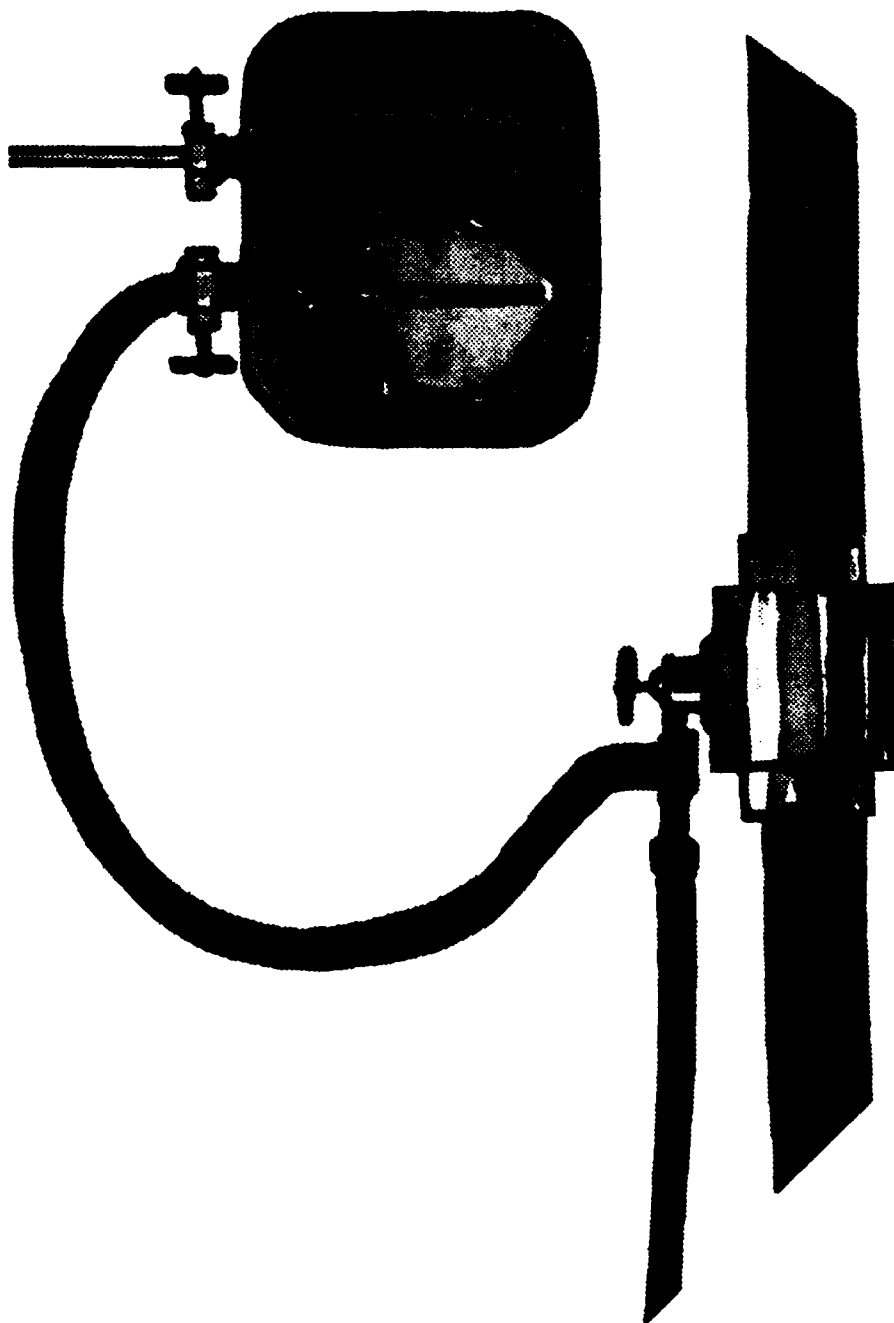


Figure 14. Cutaway View of Pneumatic Liquid Accelerator System.

compressive strengths of 3000 psi in 8 hours). With the use of Type III cement, even higher early strengths have been reported. For example, Valencia (Reference 8) reported compressive strengths of greater than 6000 psi for field samples after 8 hours. The dry-mix process is also the method which has achieved the highest ultimate strengths. Since the process gives the nozzle operator control over the mix water, an experienced nozzle operator can vary the consistency of the mix to meet field conditions. Very high strengths (more than 10 ksi compressive strengths at 28 days) have been reported for shotcrete placed by the dry-mix process. However, high early strength and high ultimate strength appear to be mutually exclusive, and care must be used when designing the mix to insure that all strength requirements are met.

There are several disadvantages of the dry-mix process, including: (1) the need for experienced crew, (2) dust generation, (3) rebound, and (4) inadequate mixing. The major disadvantage of the dry-mix process is the need for an experienced crew. While the dry-mix process can deliver the highest quality shotcrete, it can also deliver the lowest quality shotcrete. The nozzle operator must control the addition of water and therefore controls the consistency of the mix. Obviously, the nozzle operator has other concerns (in the placement of the material), and if he is distracted he can quickly produce a layer of poor quality material. One way to overcome this problem is to free the nozzle operator from some of his duties through automation of functions (this is discussed in a subsequent section). Another problem is the generation of dust. New dust collectors have helped alleviate some of the dust problems. Rebound of particles is a major concern for any shotcrete application, but is a particular problem for the dry-mix process. Rebound creates several problems. One problem is the volume of material lost (waste). Other problems develop because larger particles are more susceptible to rebound. As the larger particles rebound, the ratios of cement to aggregate and fine aggregate to coarse aggregate increase, changing the properties of the material. Inadequate mixing can be a serious problem for the dry-mix process, and can lead to localized areas of too high and/or too low water/cement ratios for proper strength gains. In addition, inadequate mixing can lead to increased rebound.

2. Wet-Mix Process Shotcrete

a. General

Mix design for wet-mix process shotcrete is similar to that for dry-mix process shotcrete, but the wet-mix process allows much more control over the mix proportioning of the delivered material. In particular, precise control of proportioning often can be used to limit rebound and dust production. Although a finer mix with relatively high slump is typical, wet-mix process shotcrete can have up to 40 percent coarse aggregate, and can be gunned in a zero slump mix with up to 3/4 inch aggregate. The mixer operator has the responsibility for mix proportioning (including water/cement ratio) in the wet-mix shotcrete process, potentially freeing the nozzle operator to concentrate on placement.

b. Equipment

There are two methods of delivering wet-mix shotcrete, pumping and pneumatic feed. Figure 15 shows a cutaway view of a positive displacement (piston) pump. The positive displacement gun uses alternating piston strokes to pump fresh concrete to the nozzle, where an air ring injects compressed air to break up and spray the material. Recent improvements in positive displacement pumping technology have made this method of delivery much more competitive with the dry-mix process. Figure 16 shows a cutaway view of a squeeze pump. The squeeze pump consists of a collecting hopper (shown on the left in Figure 16) and a pumping chamber. The collecting hopper has rotating blades to help push the concrete into the pumping tube, which leads to the pumping chamber. Inside the pumping chamber, a set of rotating rollers reduces the pressure at the intake from the pumping tube, forcing the concrete out into the material hose. The velocity of impact is often reduced for the pumping method (reducing the level of compaction). Delivery rates for pumping range from 1.5 to 12 cubic yards per hour. Both the positive displacement pump and the squeeze pump require a more plastic mix than for the pneumatic gun, shown in a cutaway view in Figure 17. The pneumatic gun uses a set of mixing paddles to push wet concrete to the material feed valve. Alternating slugs of wet concrete and compressed air are sent through the material hose to

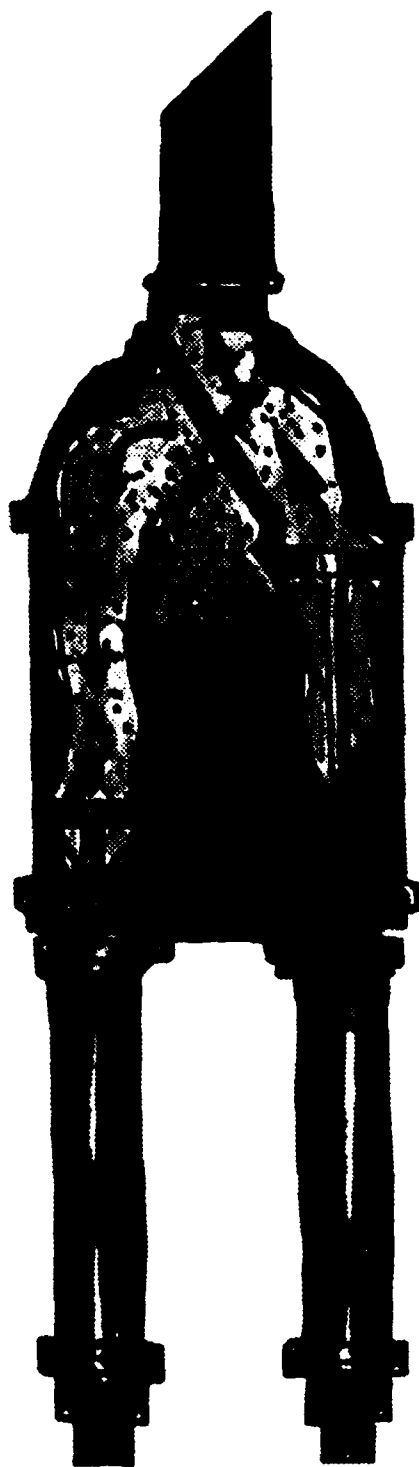


Figure 15. Cutaway View of Positive Displacement (Piston) Pump.

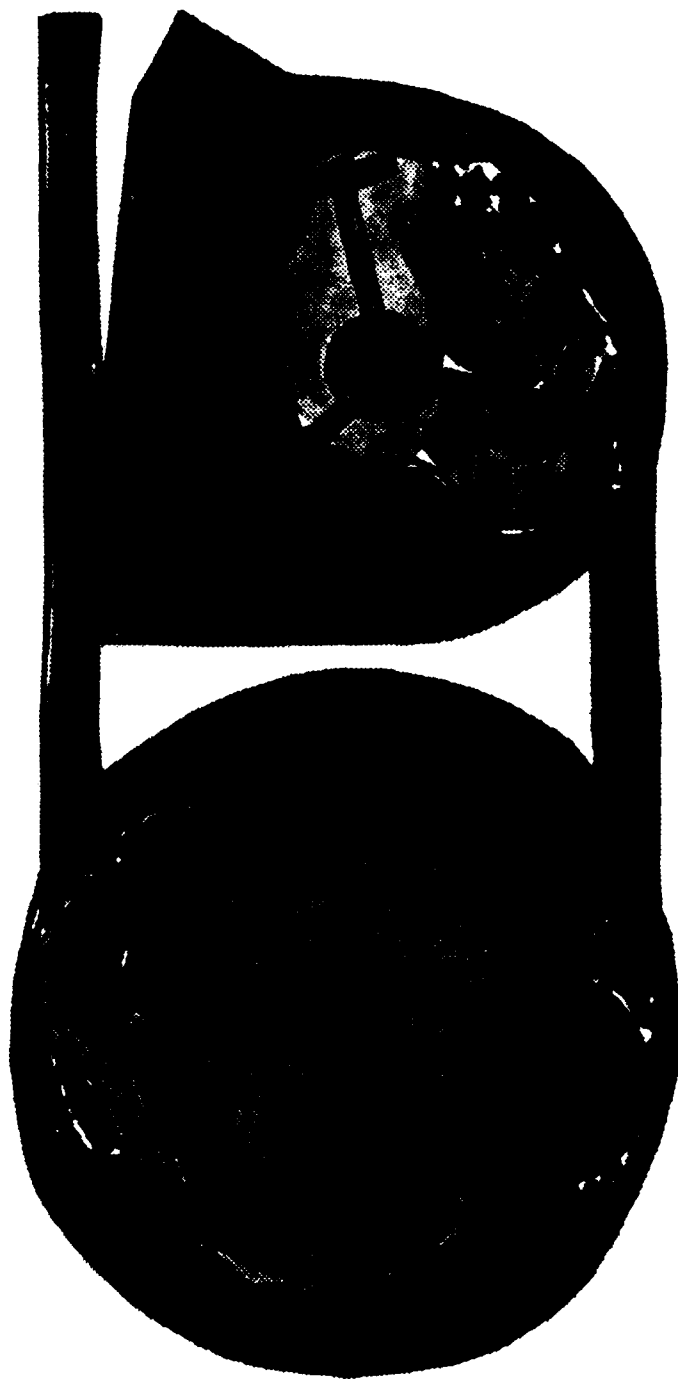


Figure 16. Cutaway View of Squeeze Pump.

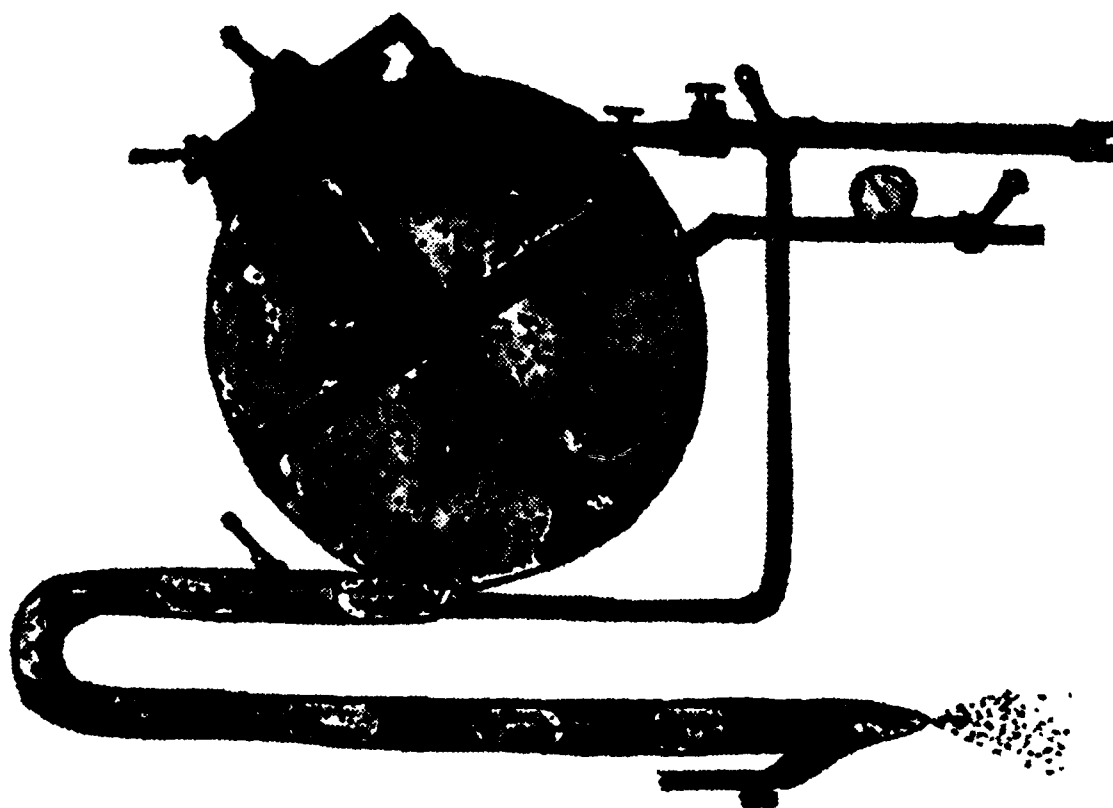


Figure 17. Cutaway View of Pneumatic Feed Gun.

the nozzle, where additional compressed air must be added to create a high-velocity impact. The length of the air slugs can be increased to reduce the weight per linear foot of hose, and to further increase the exit velocity. While this method has the potential benefit of increased exit velocity, it also has a much greater potential for clogging of lines (and other mechanical difficulties) than other methods of delivery, and has fallen into disfavor with many shotcrete designers and contractors.

A typical wet-mix nozzle is shown in Figure 18. The nozzle is equipped with an air-injection ring to force additional compressed air into the material hose and increase the exit velocity. The nozzle tip is typically made of rubber.

Liquid accelerators are typically used with wet-mix process shotcrete. The pneumatic feed system shown in Figure 14 is typical for the wet-mix process as well as the dry-mix process. Accelerators are generally less effective in the wet-mix process because the cement in the concrete has already begun to hydrate.

c. Advantages and disadvantages of the wet-mix process

The major advantages of wet-mix process shotcrete include: (1) accurate batching, (2) thorough mixing, (3) reduced duties on the nozzle operator, and (4) high overall production. Since the addition of mix water is done away from the nozzle, the mixture can be accurately batched. This allows a very consistent mix with properties which can be predicted accurately. It is also possible to thoroughly mix the batched concrete prior to pumping so that a very uniform shotcrete mix is delivered. By delivering a steady stream of uniformly mixed shotcrete material at a consistent slump, the nozzle operator can concentrate on the proper placement of material, which can result in a significant improvement in the quality of *in situ* shotcrete. The wet-mix process also has the potential for high overall (project) production rates. In some cases, concrete batch plants have been utilized for producing large quantities of premixed concrete for subsequent delivery by the wet-mix process. By designing multiple pump and gun systems, high production rates are possible. This method is rarely used, however, due to the increased cost and complexity.

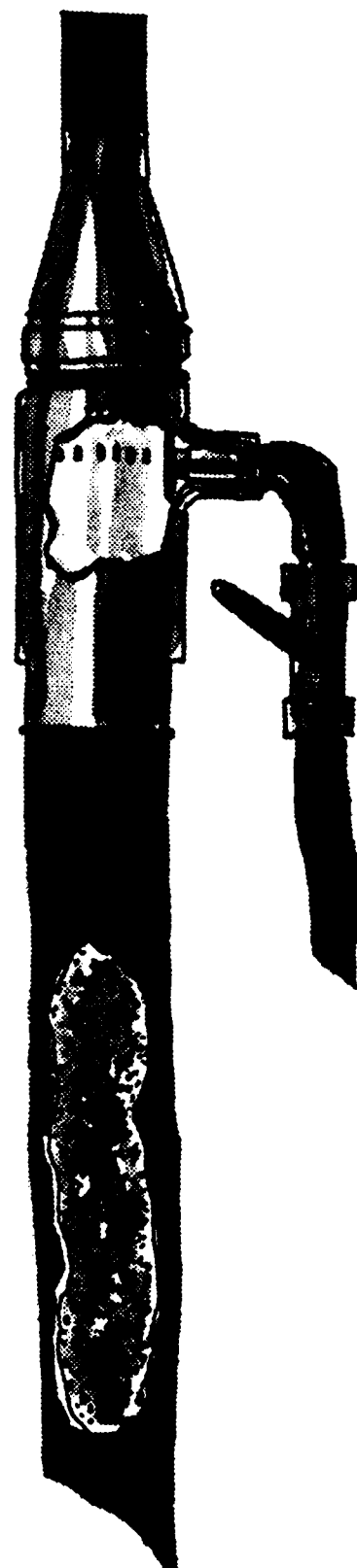


Figure 18. Cutaway View of Typical Wet-mix Nozzle with Air Injection Ring.

The major disadvantages of wet-mix process shotcrete include: (1) lower delivery velocities, (2) lower flexibility, (3) waste material, (4) lower early strengths, and (5) mechanical problems. Low delivery velocities are typically achieved for the wet-mix process, with lower compaction as the result. Although a correlation between exit velocity and material properties has not been firmly established, most authorities agree that increased delivery velocity will increase the strength and performance of the shotcrete. Since the concrete is wetted before delivery at the nozzle, there is reduced flexibility in scheduling. It is not easy to "pick up and move," as can easily be done with the dry-mix process. Similarly, waste material can be a problem, since the concrete is premixed. Since it is generally better to have too much material (as compared to too little material), some excess material will probably be wasted. High early strength in wet-mix process shotcrete has been achieved by using special cement mixtures and improved techniques for adding accelerating agents. However, in general, the wet-mix process does not produce early strengths comparable to those produced by the dry-mix process. Mechanical problems are a major difficulty for the wet-mix process. Clogging of lines can halt production and can also cause lines to be filled with hydrating concrete. Routine cleanout (as well as emergency cleanout) of equipment, including hoses, is essential to reduce mechanical problems.

SECTION III

SHOTCRETE PROPERTIES

A. GENERAL PROPERTIES

Shotcrete is pneumatically applied concrete, and therefore has similar properties and performance similar to cast-in-place concrete formed at the same water/cement ratio and density. There are, however, some noteworthy differences in shotcrete behavior when compared to cast-in-place concrete. The density of shotcrete *in situ* tends to be higher than cast-in-place concrete of similar design, particularly when placed by the dry-mix process. The density of shotcrete is related to the exit velocity of particles at the nozzle (Reference 5), but the relationship has not been characterized. Similarly, the void content and permeability of shotcrete are lower than for cast-in-place concrete of similar design. Based on actual performance studies (e.g., Reference 9), shotcrete is very durable when subjected to severe freeze-thaw conditions, the opposite of the expected behavior for a concrete with low void content. This phenomenon has been attributed to the low permeability which appears to provide a "sealing" protection. Another important phenomenon is the relationship of the *in situ* concrete to the "as delivered" concrete. *In situ* cast-in-place concrete is basically the same as the concrete which is delivered, but *in situ* shotcrete is usually much richer than the "as delivered" concrete, because the percentage of rebound by weight increases with particle size. This means that the *in situ* shotcrete tends to have a higher cement to aggregate ratio, as well as a higher fine aggregate to coarse aggregate ratio, than the "as delivered" concrete.

Compressive strength is the most common method of indexing shotcrete quality, although flexural strength is also used. The preferred method of determining shotcrete strength is by the use of core samples or beam samples taken from the *in situ* shotcrete. However, this method may be impractical in many applications, either due to difficulty in obtaining cores or in potential structural damage which could result from the sampling. The next most preferred method is the use of a slab test using a field prepared slab (this is the preferred method when large area samples are needed to evaluate

reinforcement). A frame is placed next to an area being gunned with shotcrete and is gunned at the same time, usually to a depth of 3 or 4 inches. This method has the advantage of obtaining the closest approximation of the *in situ* shotcrete without direct sampling. The shotcrete in the frame may be tested as a slab in flexure, or may be sawed into smaller specimens for testing in flexure (beams) or in compression (cubes). The compressive strength of cubes are higher than for standard cylinders of the same material, which may explain the exceptionally high compressive strengths (on the order of 10,000 psi) which are sometimes reported for shotcrete. A method which is often used for quality control involves gunning a standard size concrete cylinder into a mesh form. Ease of specimen preparation is the only advantage of this method, because the specimens formed by this method are not representative of the *in situ* shotcrete. This method can be useful in quality control if used as an comparison test, but only if other testing is used to determine the overall quality of the shotcrete.

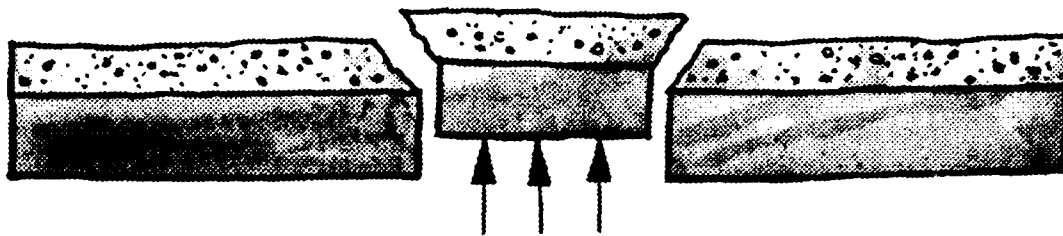
Three other tests which have been used to evaluate *in situ* shotcrete, but have not been universally accepted are the Windsor probe, the rebound hammer, and the pullout test. The Windsor probe is a penetration test which is very useful for relative strength comparisons, but the direct correlations with compressive strength must be made on a mix-by-mix basis. The rebound hammer measures the rebound of a rod forced against the surface by a spring load. This device is also useful for relative strength comparisons. The pullout test has been advocated by some researchers (e.g., Reference 10) as a way of measuring strength in the field. To perform the test, a bolt with a washer brazed to the head is embedded in fresh shotcrete. A truncated cone of shotcrete is extracted by pulling the bolt from the material through a steel ring. The result is a pullout failure stress which can be related to the compressive strength of the shotcrete. Statistical analysis on data presented by Rutenbeck (Reference 10) indicated that correlations between pullout failure stress and compressive strength were highly significant.

Shotcrete used in expedient repair situations would often be in a planar configuration. Fernandez-Delgado, *et al.*, reported on the failure mechanisms of shotcrete in planar configurations, based on large-scale slab tests, as illustrated in Figure 19. The large-scale tests used a slab with a square block at the center which was sprayed with shotcrete and then loaded to failure. These tests are of particular interest because they are directly

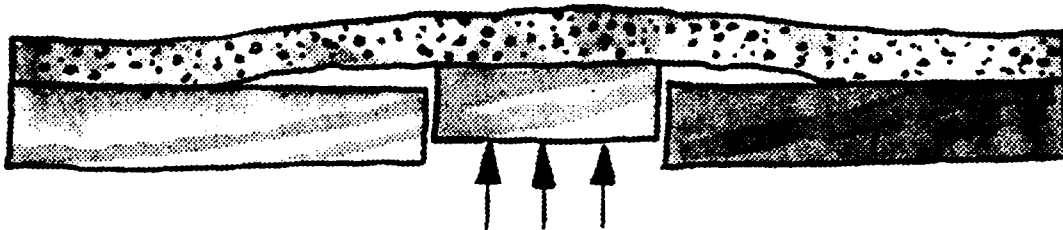
analogous to the case of a shotcrete-repaired breach which is subsequently loaded (for example, by a bomb or a fragment). The major difference between the slab tests and expedient repair applications is that the loading for the expedient repair application would most likely come from the other side of the slab. Figure 19(a) illustrates a diagonal tension, or punching, failure. When loaded as shown in Figure 19(a), this type of failure will occur when the bonding of the shotcrete is strong. This type of failure may also occur if the slab is loaded from the reverse side of the slab. The failure mechanism shown in Figure 19(b) is an adhesion failure, which is controlled by the condition of the underlying bond interface. This type of failure is less important for most expedient repair applications, because it will not occur when the loading is applied from the reverse side of the slab. Figure 19(c) illustrates the third common failure mechanism for planar configurations, which is a bending, or flexural, failure. This type of failure depends on the flexural strength of the shotcrete, and can also occur when the slab is loaded from the reverse side (if the area being loaded is small compared to the area of the breach). An examination of the primary failure mechanisms shows that the most important properties for shotcrete used in expedient repairs are not related to compressive strength, but to tensile strength and ductility. Testing to determine suitability of shotcrete designs or mixes for expedient repair purposes should, therefore, concentrate on tensile/flexural properties rather than relying on compressive strength as the index parameter.

B. HIGH EARLY STRENGTH SHOTCRETE

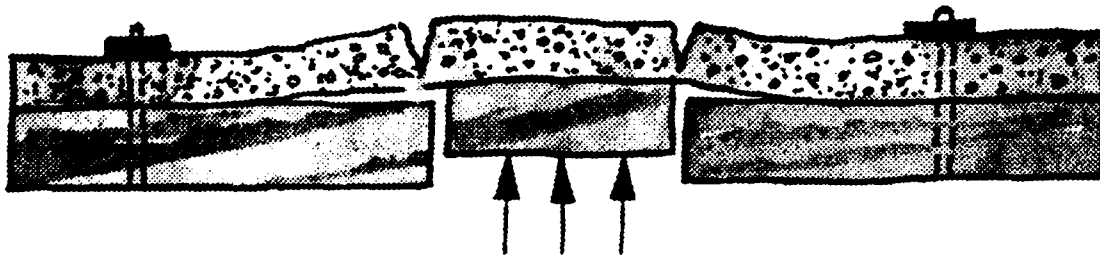
The potential for high early strength has traditionally been a strong selling point for shotcrete. High early strength is commonly needed for ground support situations, such as tunnels or swimming pools, but is also needed in expedient repair situations. High early strength is typically achieved by the addition to the mix of accelerating admixtures, but may also be achieved by the use of regulated set cement. Early setting (stiffening) is also commonly desired for the applications which require high early strength. It is often possible to achieve both rapid setting and high early strength with the addition of a suitable accelerating admixture.



(a) Failure in Diagonal Tension (Punching Failure).



(b) Failure in Adhesion (Bonding Failure).



(c) Failure in Bending (Flexural Failure).

Figure 19. Typical Failure Modes for Large-scale Slab Tests.

1. Accelerating admixtures

Accelerating admixtures may be in either the dry-mix process or in the wet-mix process. However, most authorities (e.g., Reference 11) agree that the accelerating admixtures work better with the dry-mix process. Addition of admixture in the wet-mix process is more difficult to control and the accelerator is often ineffective due to hydration of the mix before the addition of the accelerator. It is not uncommon to use accelerators in the wet-mix process to induce an early stiffening (initial set) without anticipating an accelerated strength gain.

2. Wet versus dry accelerators

The accelerating admixtures commonly used in shotcrete construction are normally classified as either wet (liquid) or dry (powder). Figure 14 (see page 19) shows a cutaway view of a typical liquid accelerator system. The liquid accelerator system can be used in the wet-mix process, but is much more effective in the dry-mix process since the accelerator can be added directly to the mix water. There are two common liquid accelerators, soluble aluminates and soluble silicates (also known as waterglass). Figure 12 (see page 17) shows a pictorial drawing of a typical dry-powder dispenser. A cutaway view of the dry-powder dispenser installed on a calibrated shotcrete gun is shown in Figure 13 (see page 18). The accelerator is fed into the gun by an auger. The rate of feed (speed of the auger) is adjusted by a control box which is, in turn, controlled by signals from the shotcrete gun motor. Dry accelerators are typically restricted to the dry-mix process, because of clumping of the powder when added to wet mixes. The common types of dry accelerators are soluble carbonates, soluble aluminates, and a combination of both.

3. Inorganic versus organic accelerators

Another way of characterizing accelerating admixtures is by their chemical nature, either organic or inorganic. The chemical nature of the admixture has a controlling effect on properties of the *in situ* shotcrete, as well as on long-term performance.

Inorganic accelerators include soluble aluminates, soluble carbonates, and soluble silicates, and typically induce well-known chemical reactions (Reference 12). Soluble aluminates combine with gypsum, allowing the tricalcium aluminate in the cement to flash set, providing early stiffening. Soluble silicates induce quick-setting by precipitating as calcium silicate, but reduce ultimate strengths significantly by their interference on the cement/water reaction. Soluble carbonates will accelerate early strength gain but tend to retard the effect of aluminates on initial set. The typical inorganic accelerator uses a combination of carbonates and aluminates to induce the desired properties. The proportioning of carbonates and aluminates must be varied for different cements.

Nearly all accelerators currently available are of the inorganic type described above, but newer organic accelerators have the potential for improving the properties of high early strength shotcrete. The organic accelerators are often proprietary and very expensive. Organic accelerators solubilize the lime and ettringite which normally precipitate and interfere with the cement/water reaction. Since these accelerators do not change the basic cement/water reaction, there is no significant strength penalty.

Figures 20 and 21, based on data presented by Schutz (Reference 12), show the effects of admixtures on setting times (ASTM C 403) and on ultimate strength, respectively. These figures clearly illustrate the differences between inorganic and organic accelerators. From Figure 20, both accelerator types decreased setting times and roughly equivalent amounts of accelerator (3 pounds inorganic per sack versus 1/3 gallon organic per sack) produced roughly equivalent final setting times. However, much more organic accelerator (3/4 gallon per sack) was needed to achieve an initial setting time roughly equivalent to the inorganic accelerator (at 3 pounds per sack). Figure 21 emphasizes the strength penalty typically associated with inorganic accelerators and the superior ultimate strengths which can be achieved with organic accelerators.

The trends reported by Schutz and shown in Figures 20 and 21 are confirmed by numerous other authors. For example, Blank (Reference 13) states that with careful laboratory compatibility testing, high early strength (500 and 1000 psi at 3 and 5 hours, respectively) and rapid setting (initial and final set at 3 and 12 minutes, respectively) can be achieved using 2 to 3 percent of conventional (inorganic) admixture, with a loss in ultimate

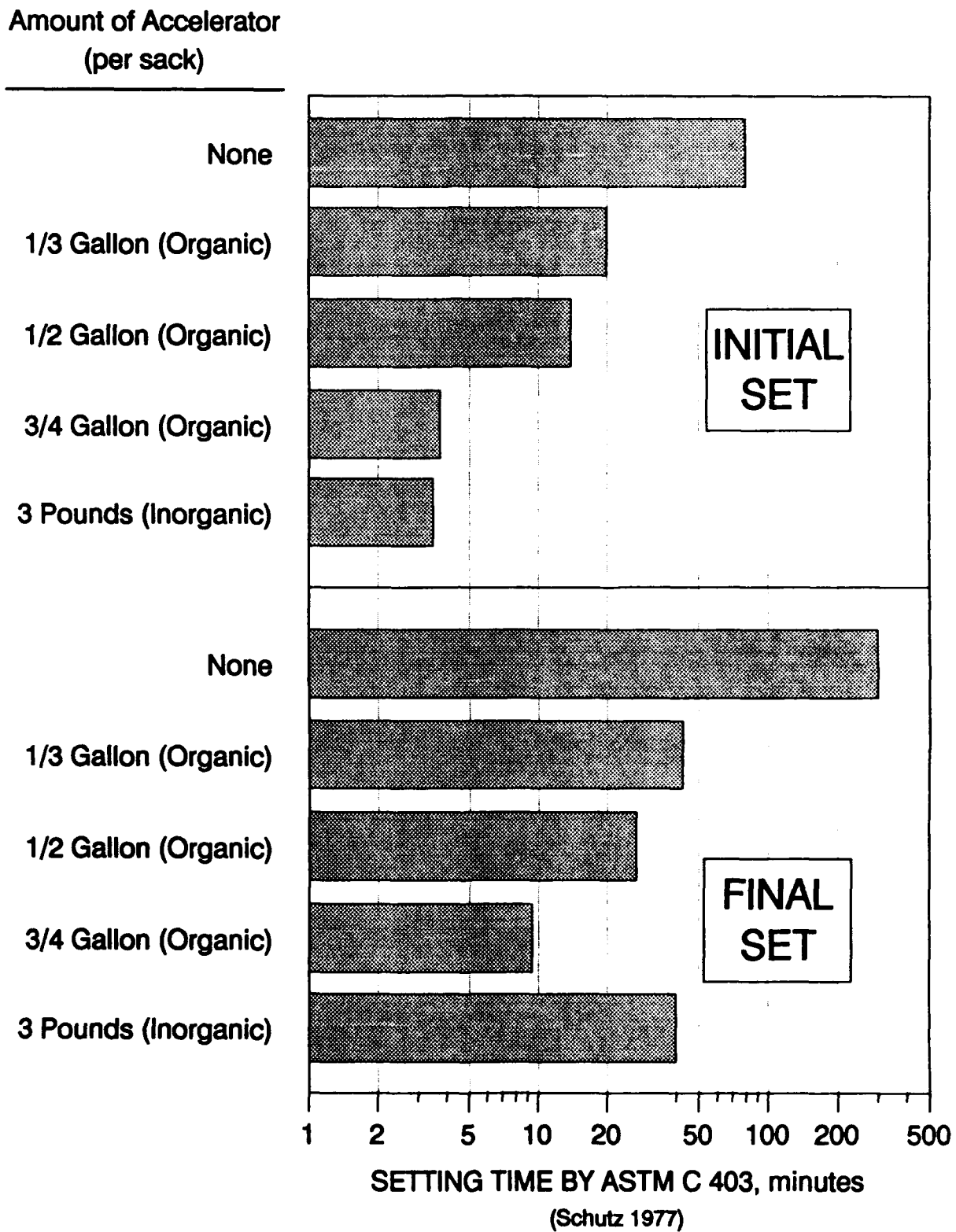


Figure 20. The Effects of Accelerating Admixtures on Setting Times.

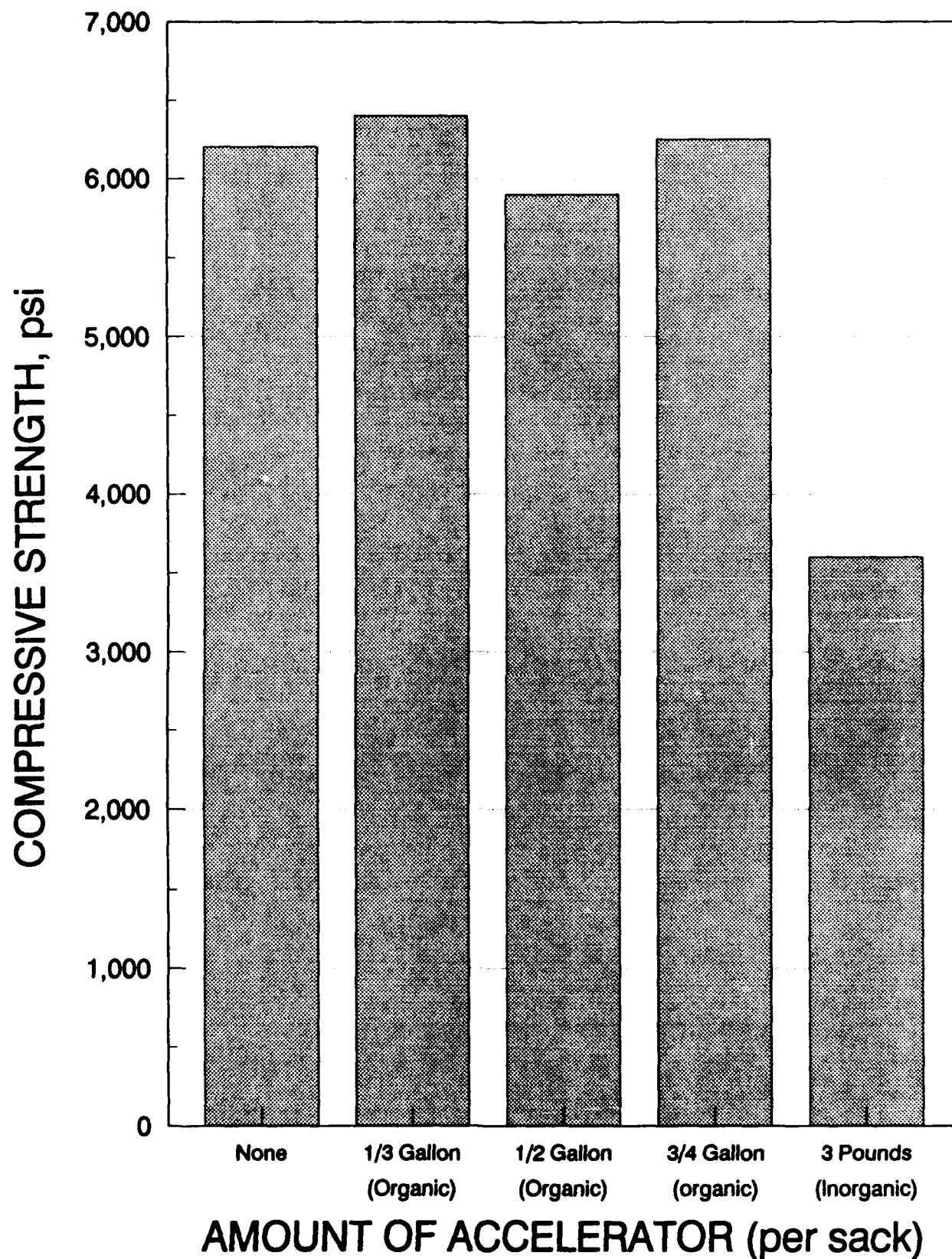


Figure 21. The Effects of Accelerating Admixtures on Ultimate Strength.

strength of about 25 percent at 28 days and about 15 percent at 90 days. Similarly, Bauder (Reference 14) states that almost flash set can be achieved with aluminate (inorganic) admixtures, with a loss in ultimate strength of 10 percent to 40 percent depending on dosage (2 percent to 12 percent of cement weight).

4. Regulated-set cement Shotcrete

The use of regulated-set cement (i.e., rapid setting cement) instead of accelerating admixtures has been endorsed by some authorities (e.g., Reference 15). Regulated-set cement is useful when the exact amount of needed concrete is known, and a rigid schedule can be followed. Parker (Reference 16) did field research on regulated-set fiber-reinforced shotcrete and found that compressive strengths of 1000 psi could be achieved in 1 hour. Regulated-set cement utilizes calcium fluoroaluminate and initial set can be achieved in less than 10 minutes. The advantages of regulated-set shotcrete include: (1) no accelerating admixture is required, (2) early strength of regulated-set shotcrete is much higher than for conventional shotcrete, and (3) there is no reduction in the 28-day compressive strength. Although regulated-set cement is much more costly than conventional cement, there are other potential problems which would almost prohibit its use for expedient repair. For example, procedures must be implemented for emergency dump and clean out in the event of work stoppages (otherwise, the concrete will set up in the equipment). In addition, the aggregate and cement must be conveyed separately and continuously mixed at the heading (since the aggregate could contain moisture which would start hydration), and also water heaters are often needed to heat the water to the correct temperature.

C. SPECIAL SHOTCRETE MIXTURES

1. Fibrous Shotcrete

Of all special shotcrete mixtures, steel-fiber-reinforced (or fibrous) shotcrete has the greatest potential for expedient repair purposes. The following quotes (Reference 17) are typical of conclusions from those who have used fiber-reinforced shotcrete. "The addition of steel fibers to

shotcrete makes it almost an ideal material for concrete repair and renovation." "... steel fibers make shotcrete a tenacious material." "Steel fiber shotcrete resists far greater impact and shock ... than plain shotcrete." "Because of its increased resistance to blasts and shocks, ... fiber shotcrete is highly recommended for military structures." In a state-of-the-art report, the American Concrete Institute (Reference 18) concluded that fiber reinforcement in shotcrete generally improves material properties including ductility, toughness, flexural strength, impact resistance, fatigue resistance, and compressive strength. Although other fiber types are available, steel fibers are the most commonly used for shotcrete. Figure 22 shows typical data for tensile strength tests on shotcrete both with and without fiber reinforcement. A typical unreinforced shotcrete specimen (or even a conventional concrete specimen) will fail quickly after the first cracking, showing a relatively low ultimate tensile strength (typically 400 to 500 psi) and complete failure at a very low strain level (typically less than 0.1 percent strain). By the addition of a small amount of steel fibers, the stress required to induce cracking is increased, thereby increasing the ultimate strength. More important, the specimen retains a significant residual strength even after the initial cracking (typically 200 to 300 psi) which is directly related to the pull-out strength of the steel fibers. Strain without failure occurs until the fibers actually pull out of the cement binder matrix (typically at about 2 percent strain), therefore producing a ductile material. With a high fiber content, the concrete does not crack until the pull-out strength of the fibers has been exceeded (typically at about 1000 psi). This means that even though the ultimate strength is increased, the ductility is retained. Similar results can be shown for compressive strength (although this is less important for expedient repairs).

Existing equipment with little or no modifications can be used for the application of steel-fiber shotcrete, when special fibers are used. These have deformed ends and are glued together to reduce the "balling" typically reported for these mixes. In addition, specialized equipment is available for the addition of fibers and the application of fibrous shotcrete (Reference 18).

Fibrous shotcrete has performed well in the rehabilitation of "honeycomb" areas in waterways repaired by the US Army Corps of Engineers

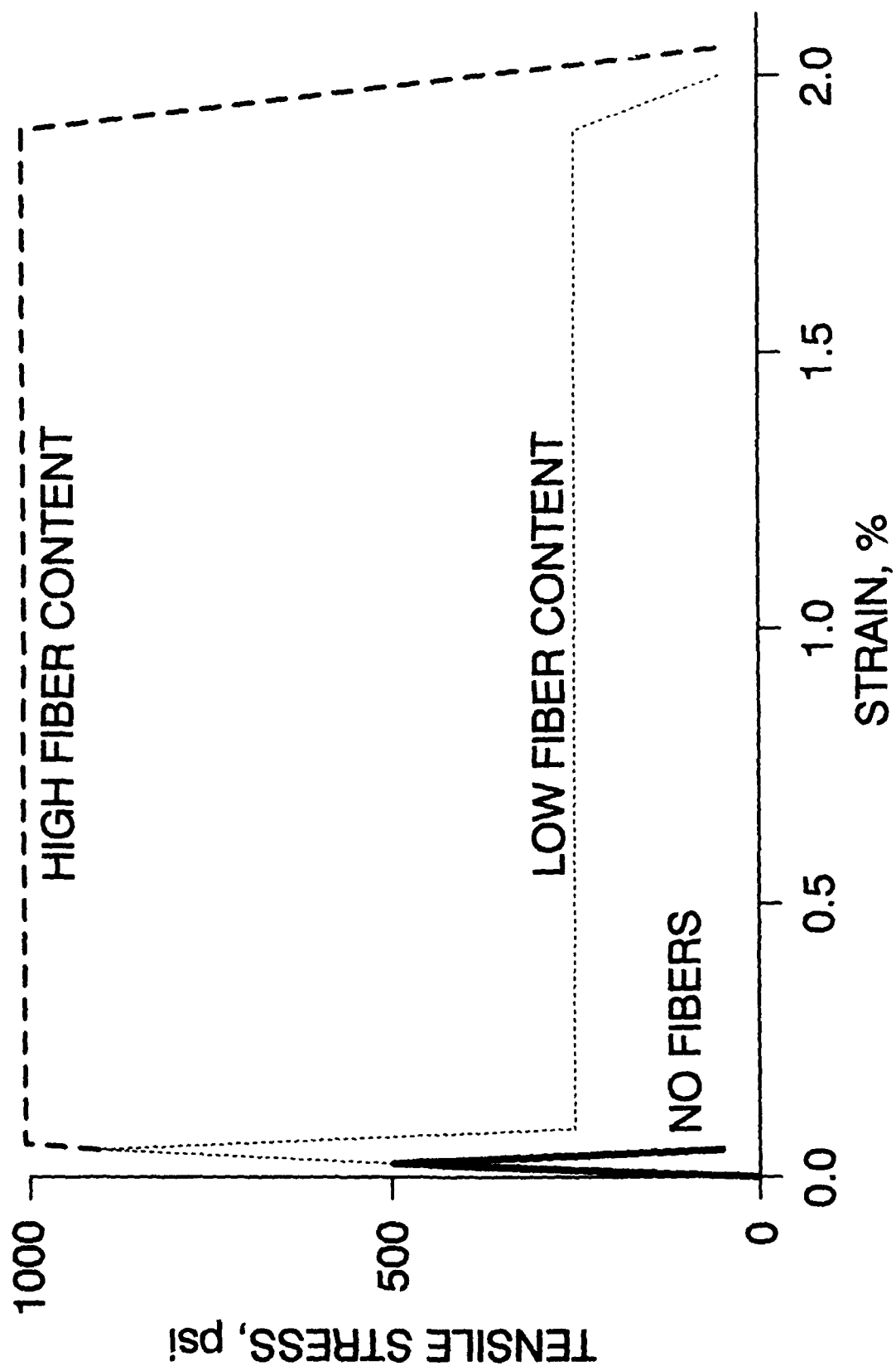


Figure 22. Typical Tensile Strength Data for Steel-fiber-reinforced Shotcrete.

(Reference 19), even in extreme climatic conditions. The fiber-reinforced shotcrete had low permeability compared to conventional concrete, which limited corrosion. This finding was supported by Morgan (Reference 20), whose studies of fibrous shotcrete in severe environments have shown that carbon steel fibers will not oxidize significantly as long as crack widths are less than 0.003 inch. In addition, much of the composite strength may be retained for cracks up to 0.012 inch, because the fibers can tolerate significant reduction in diameter with minimal effects (since their main reaction is by pull-out).

Kaden (Reference 21) reported on the use of fiber-reinforced shotcrete in the Ririe Dam Relocation. For that project, the reduced thickness of fibrous shotcrete resulted in a 40 percent cost savings over conventional shotcrete with wire fabric reinforcement. More importantly, the fiber-reinforced shotcrete had improved tensile strength and strain to failure, showed less cracking, and provided micro-reinforcement across discontinuities (which agrees with findings by Scanlon, as previously discussed). The Ririe Dam mix used 240 pounds of steel fibers (16-mil diameter by 3/4-inch length) per cubic yard and produced 28-day flexural strengths of 900 psi with increased ductility (Reference 22).

Gilbride, et al. (Reference 23) described structural repairs at the Port of Saint John in extreme marine conditions. The berth faces (wharves) had deteriorated due to freeze-thaw, alkali-aggregate reaction, and marine salt reaction. The repair method used wet-mix, steel fiber-reinforced, silica fume shotcrete, anchored with grouted dowels. This method provided a thick veneer of dense impermeable concrete over an essentially weak and permeable concrete base. Restrained drying shrinkage cracks occurred in the surface after about a year of service, but were not considered a serious problem. A sealing coat of shotcrete was applied to protect the underlying concrete from any intrusion of marine material.

The list of successful uses of fiber-reinforced shotcrete for structural repairs is a long one. The few examples given herein emphasize that repairs similar to those needed in many expedient repair situations have been done in the past with great success. The increased ductility and tensile strength of fiber-reinforced shotcrete make it almost an ideal expedient repair material.

2. Latex Shotcrete

Shotcrete which uses latex modifiers is available and has some desirable properties, mainly improved durability and improved bonding capability. Durability is improved because the latex bonds with the cement paste and the flexibility and tensile strength of the latex modifier limits the formation of microcracks during curing (reducing the permeability). Latex modifiers reduce the ultimate strength of shotcrete, but bonding is improved and the latex-modified shotcrete can tolerate larger strains than conventional shotcrete. Impact tests (Reference 24) indicate that about 5 times more blows were required to develop the first crack compared to conventional shotcrete. Traditional mix designs may need modification if latex is to be added, since latex-modified shotcrete mixes are designed for maximum durability instead of maximum strength. Flexural strength and absorption tests should be used for quality control instead of strength tests, since addition of latex does not improve the compressive strength.

It would seem that latex-modified shotcrete would be an ideal expedient repair material, but difficulties in mixing and applying the material in an expedient repair scenario must be considered. Adequate mixing of latex modifiers requires specialized equipment and handling procedures. In addition, special care must be taken when applying the mix to a repair surface. The surface of latex-modified shotcrete develops a film which must be removed/broken before adding more layers, or subsequent bonding cannot be achieved. Brooming will break the film unless the final set is established, otherwise sandblasting or waterblasting is required. Latex-modified shotcrete may be a good alternative for longer term repairs, but the practical difficulties involved in its use virtually eliminate it from consideration as an expedient repair material.

3. Polymer Shotcrete

Polymer shotcrete consists of aggregate and monomer mixed together, and subsequently polymerized at ambient temperatures following placement of the material. The principal difference between polymer shotcrete and conventional shotcrete is that a polymeric binder is used in lieu of Portland cement and water. The dry-mix process is typically used for application of

polymer shotcrete. Graham (Reference 25) reported on the use of polymer shotcrete with emphasis on the cohesive qualities of the mix, the properties of the cured material, and the low temperature performance of the polymerization system. Screening tests indicated that a suitable monomer system contained 72 percent by weight MMA (methyl-methacrylate), 13 percent by weight TMPTMA (trimethylolpropane trimethacrylate), and 15 percent by weight Acryloid A-11 (primarily polymethyl methacrylate). Rapid cure of the monomer system was achieved by adding a polymerization catalyst-promoter system composed of benzoyl peroxide as a catalyst and the promoter, n, n, dimethyl-p-toluidine in concentrations of 2 percent each by total monomer weight. Aggregate gradations were selected which would provide a cohesive mix with minimum rebound and a sound finished product. Two shotcrete application techniques were used. The first used modified shotcrete equipment to mix and deliver a final product. The second used a staged approach, with a heavy monomer spray followed by an application of dry aggregate to provide a laminating effect. In general, the polymer shotcrete had compressive strength exceeding conventional shotcrete.

As with latex-modified shotcrete, polymer shotcrete might appear attractive for expedient repair scenarios; however, there are strong reasons why this method should not be used for expedient repair. Special equipment and procedures are needed for handling the materials. In addition, many of the polymers can create environmental hazards before and after use. More detrimental to potential expedient repair efforts is the potential for accidental catalyzation of polymer which could render repair equipment useless. However, the most important reason for not using polymer shotcrete in a postattack environment is that the polymers used are highly volatile and could react violently, creating an unnecessary safety hazard in an environment which may already contain fires, chemicals, or explosives.

SECTION IV

AUTOMATED SHOTCRETE EQUIPMENT

A. EXISTING EQUIPMENT

The use of automation in the shotcrete process has numerous advantages. The two most important advantages of automated shotcrete equipment are: (1) the nozzle operator can be relieved of much of the repetitive functioning typically associated with shotcrete application, allowing most of his concentration to be put on delivering top-quality shotcrete and (2) since the nozzle operator does not have to be near the nozzle tip, measures to improve safety in hazardous situations can be easily implemented. The most common use of automation has been in tunnel linings. Monaghan, et al. (Reference 26), described a rotary system used to remotely control the placement of shotcrete tunnel linings. The system allowed complete remote control of the nozzle operation using a thickness gage and video monitoring system. With the remote control, the operator could control gross movements of the nozzle, including the attitude, as well as the rate and direction of rotation. In addition, the operator could remotely control the flow rates of shotcrete, accelerator, and water. Required equipment was a "Concrete Mobile" to deliver the mix, a shotcrete machine to meter and inject the shotcrete mix (as well as screening the oversize aggregate), hoses to convey the mix, water pumping system, electrical cable and water hose reels, a headsheave support system, a winch and drum system to spool the wire rope supporting the shotcrete assembly, and an operator control console. Operation of the entire system required only three people (one each for the control system, the shotcrete machine, and the Concrete Mobile). A demonstration study showed a cost savings of almost 25 percent with a tripling of production rate and improved safety.

Many of the advantages of automated rotary systems have been incorporated into more general-purpose automated equipment. A Swedish company named Stabilator has been a leader in the development and use of general purpose automated shotcrete equipment. Figure 23 illustrates an automated shotcrete system being used to stabilize the ceiling of a tunnel before removal of blast rubble. The equipment shown is a Trixer (combined

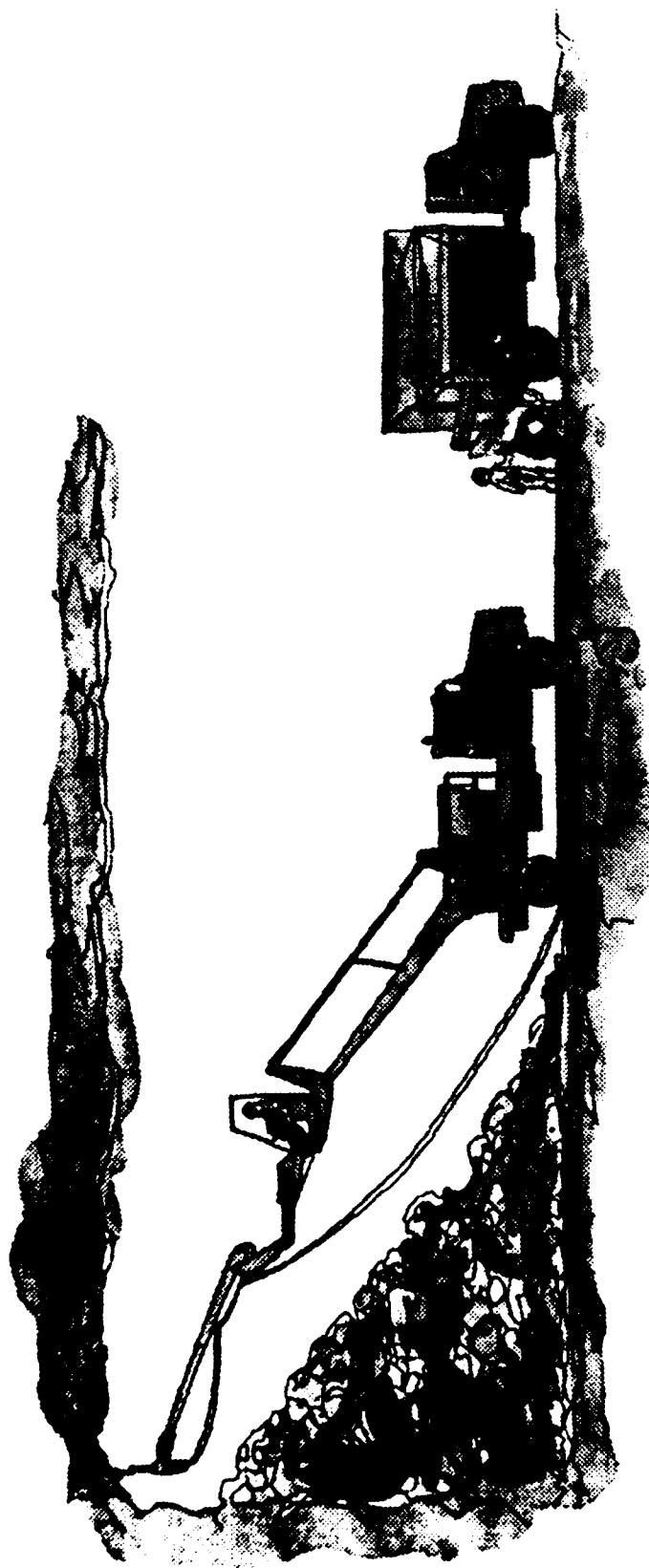


Figure 23. Use of the Trixer and the Mini-Robot (Manufactured by Stabilator).

transportation-mixing unit) and a Mini-Robot. The Trixer automates the proportioning, mixing, and gunning functions with a single truck-mounted unit. The Mini-Robot allows remote application of shotcrete using an extendable robot arm to control the nozzle. The robot arm has its own hydraulic system, so it can be easily moved between carrying systems. The basic sweeping motion has been automated, freeing the operator to concentrate on other things. A platform mount allows lateral movement of the system. The operator can leave the machine and control the arm with a small control box. Along with freeing the operator for other activities (or for increased safety), the remote control allows the operator to avoid vision problems caused by excessive material rebound. The operator can therefore apply all his concentration on dispensing a quality mix. A fiber-proportioning-and-dispensing unit is also available which will allow the use of steel-fiber-reinforced shotcrete with the automated equipment. Laboratory studies (Reference 27) indicated the best fiber for use with the remote delivery system was wavy, with length of 20 mm and diameter of 0.35 mm. Tensile strength and flexural strength were increased by 50 percent and 180 percent, respectively. The application rate for the above tests was 2.3 percent by volume, but because of rebound the actual content was 1.34 percent by volume. Field applications (Reference 27) of the robot-applied fiber-reinforced shotcrete had high tensile strength with good flexibility (low cracking) and was therefore recommended for temporary reinforcement and for use as a protective coating to prevent flow of water and/or gases (analogous to expedient repair applications).

A Robot-Trixer (Reference 28) is shown in Figure 24. The Robot-Trixer is a combined unit which performs all of the functions of the systems shown in Figure 23. However, all of the functions have been somewhat scaled down. For example, the material capacity is only 3.6 cubic yards and the nominal mixing capacity is 7 cubic yards per hour. In addition, the robot arm has a lessened range of motion compared to the Mini-Robot. The Robot-Trixer can travel at 11 mph.

B. MASERV CONCEPT

Figure 25 illustrates a concept, developed by the author, of an advanced repair vehicle called MASERV (Mobile Automated Shotcrete Expedient Repair Vehicle). The MASERV concept includes all of the automated functions of the

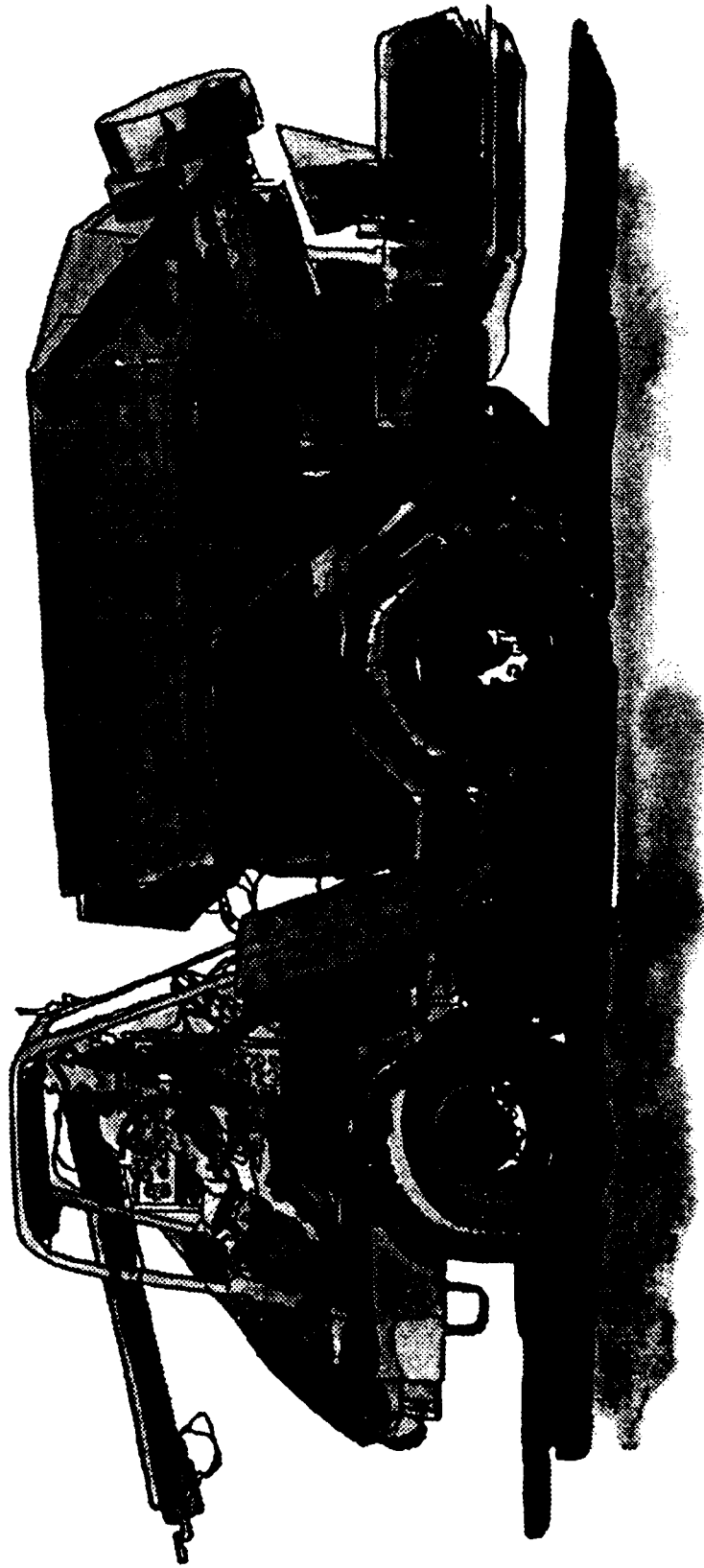


Figure 24. Pictorial Drawing of Robot-Triaxer (Manufactured by Stabilator).

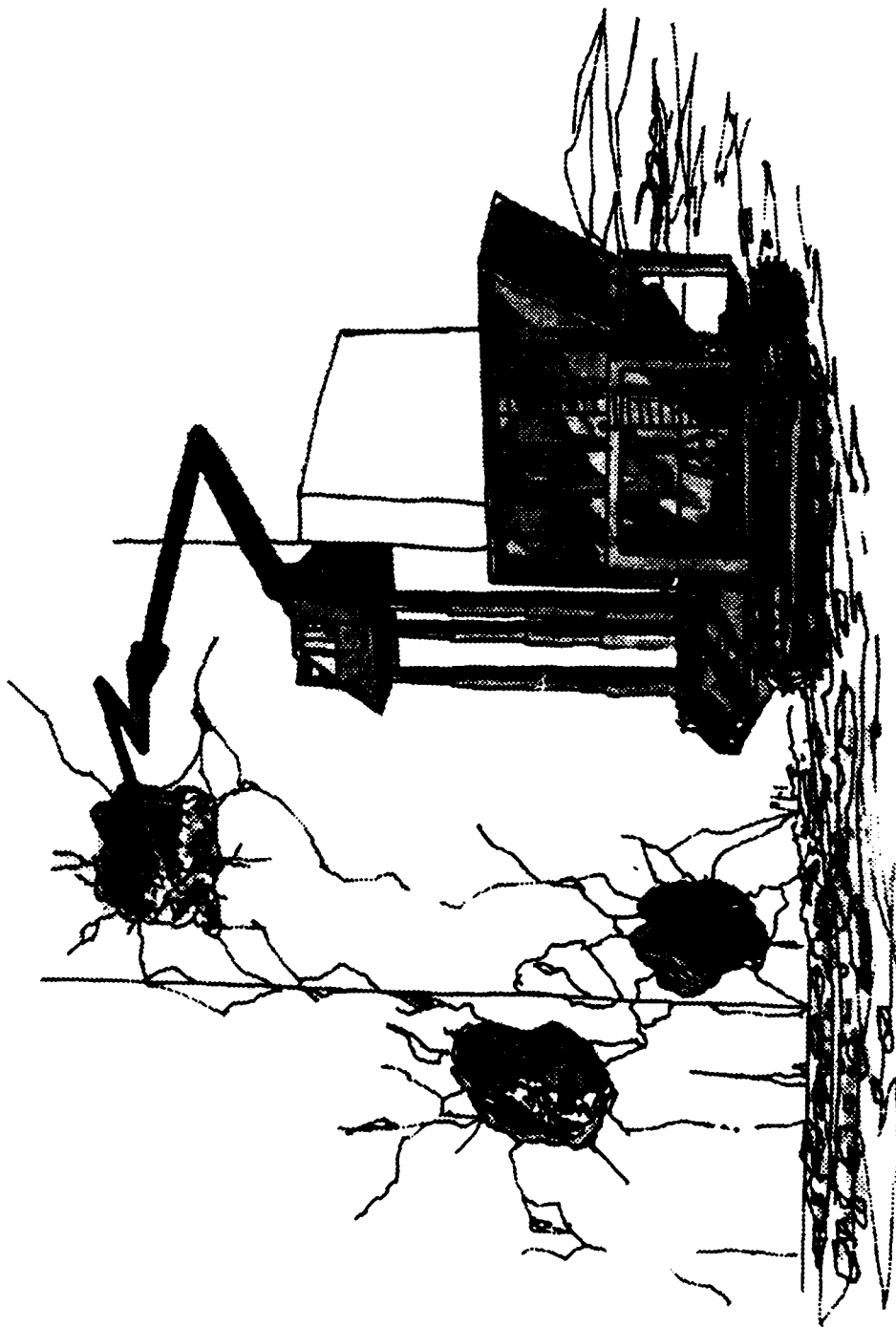


Figure 25. Concept Slide of MASERV (Mobile Automated Shotcrete Expedient Repair Vehicle).

Robot-Triker with some additional advanced features. The MASERV is track-mounted and armored for use in a postattack environment. It can carry large volumes of materials (like the Triker) and has a highly versatile robot arm attached to a cab which can be hydraulically lifted to allow repairs on upper floors of structures. The concept illustration includes repair workers equipped with chemical garb who are working inside the building to provide backing material for the shotcrete spraying. This is better described in Section V.A. (Concept of Expedient Repair with Shotcrete). Figure 26 illustrates the addition of an environmental shield which would be used to stop wind and/or rain from interfering with the shotcrete application. A close-up view of an environmental shield equipped nozzle is shown in Figure 27. While the MASERV concept shown in Figures 25-27 is clearly more advanced than the equipment currently available, it is likely that some version of this vehicle (with many of the capabilities shown) could be built almost immediately if funding were available.

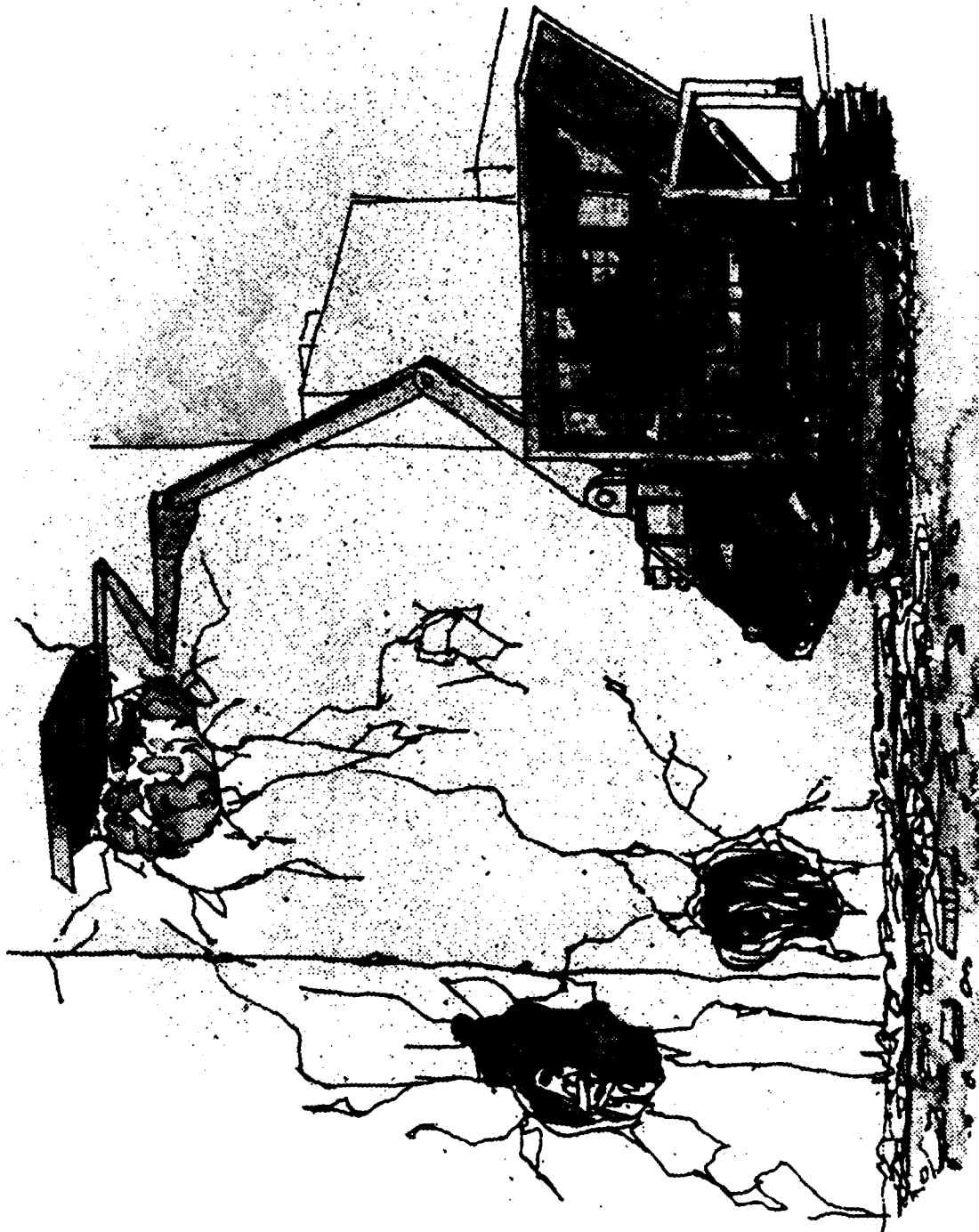


Figure 26. Concept Side of MASERV (Mobile Automated Shotcrete Expedient Repair Repair Vehicle) Equipped with Environmental Shield.

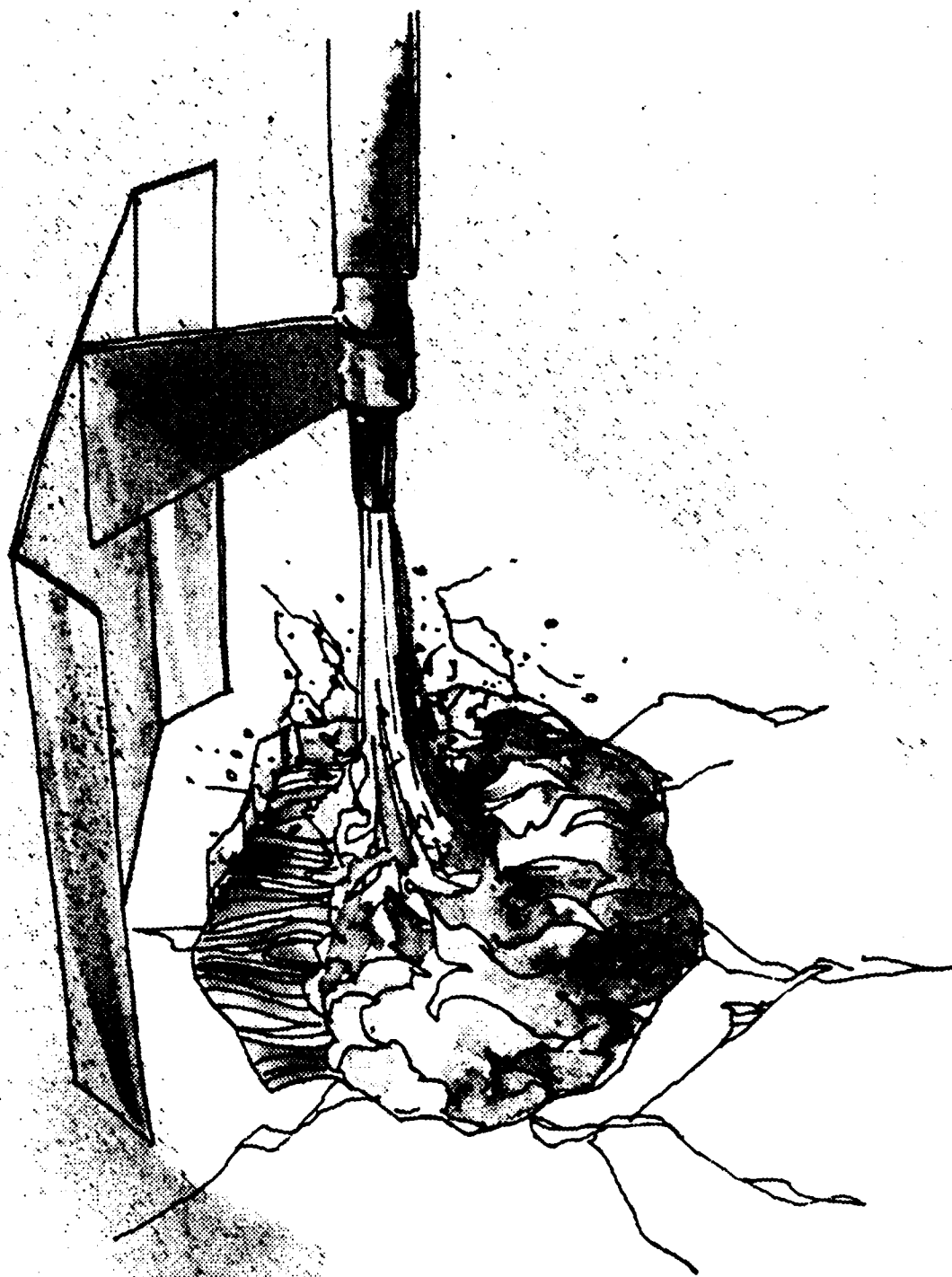


Figure 27. Close-up View of Nozzle Equipped with Environmental Shield.

SECTION V

PROPOSED FIELD TEST

A. CONCEPT OF EXPEDIENT REPAIR WITH SHOTCRETE

Figures 28-30 illustrate the concept of an expedient repair with shotcrete in a postattack environment. Figure 28 illustrates a damaged mission-critical facility undergoing a postattack damage assessment. The damaged area is prepared for a shotcrete repair, as shown in Figure 29. The preparation method shown in Figure 29 utilizes plywood as a backing material for the shotcrete application. Other materials may be used, since shotcrete can be shot against virtually any surface which provides even a minimum of resistance. Figure 30 illustrates the completion of the shotcrete repair. In Figure 30, the large breach has been reinforced with retrofitted reinforcing steel before the shotcrete application.

B. DESCRIPTION OF FACILITY

Figures 31-33 show the test facility proposed for use in the validation of shotcrete use for expedient structural repair. The proposed test facility is the cast-in-place building vulnerability test target at the C-74 Test Site, Eglin Air Force Base, Florida. Figure 31 shows the design for the undamaged structure. The structure consisted of two three-story buildings, structurally isolated by a styrofoam partition. Each of the buildings was designed as a "box" structure, with four rooms on each floor. Figure 32 shows the current condition of the structure after routine testing by a Mark 82 bomb, which hit the west side of the structure and destroyed the entire western building. The eastern building sustained damage on the lower western exterior walls and on a column which separated those exterior walls. Figure 33 is a pictorial illustration of the current (damaged) structure. Several features of interest are available on the structure which could be used for shotcrete testing. There is a large opening in the front room of the remaining (eastern) structure, where the wall has been "blown away." There is also a slab standing next to the building which has been used in a penetration test and

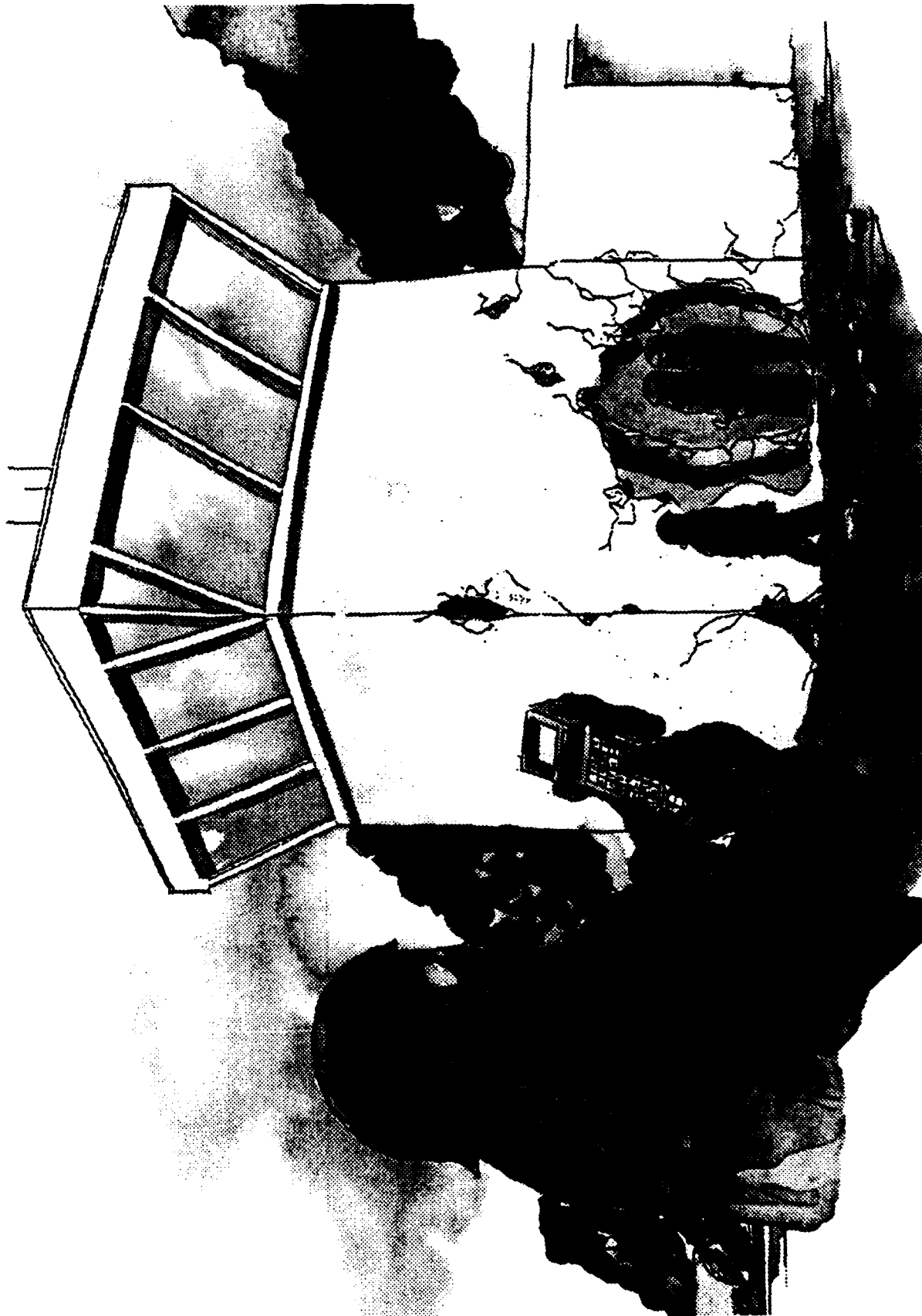


Figure 28. Concept Illustration of a Damaged Mission-critical Facility.

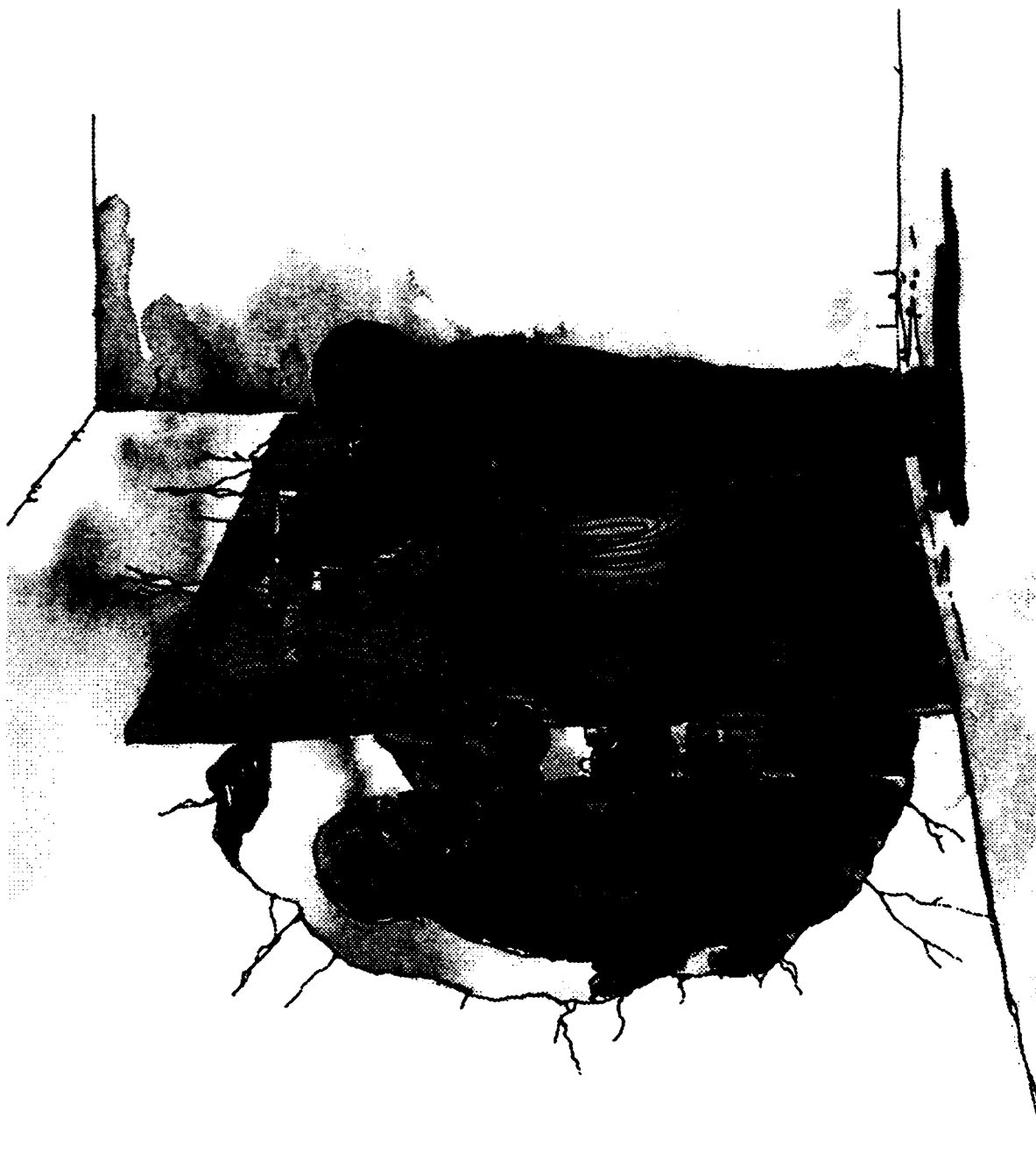


Figure 29. Preparation for a Shotcrete Repair in a Postattack Environment.



Figure 30. Completion of a Shotcrete Repair in a Postattack Environment.

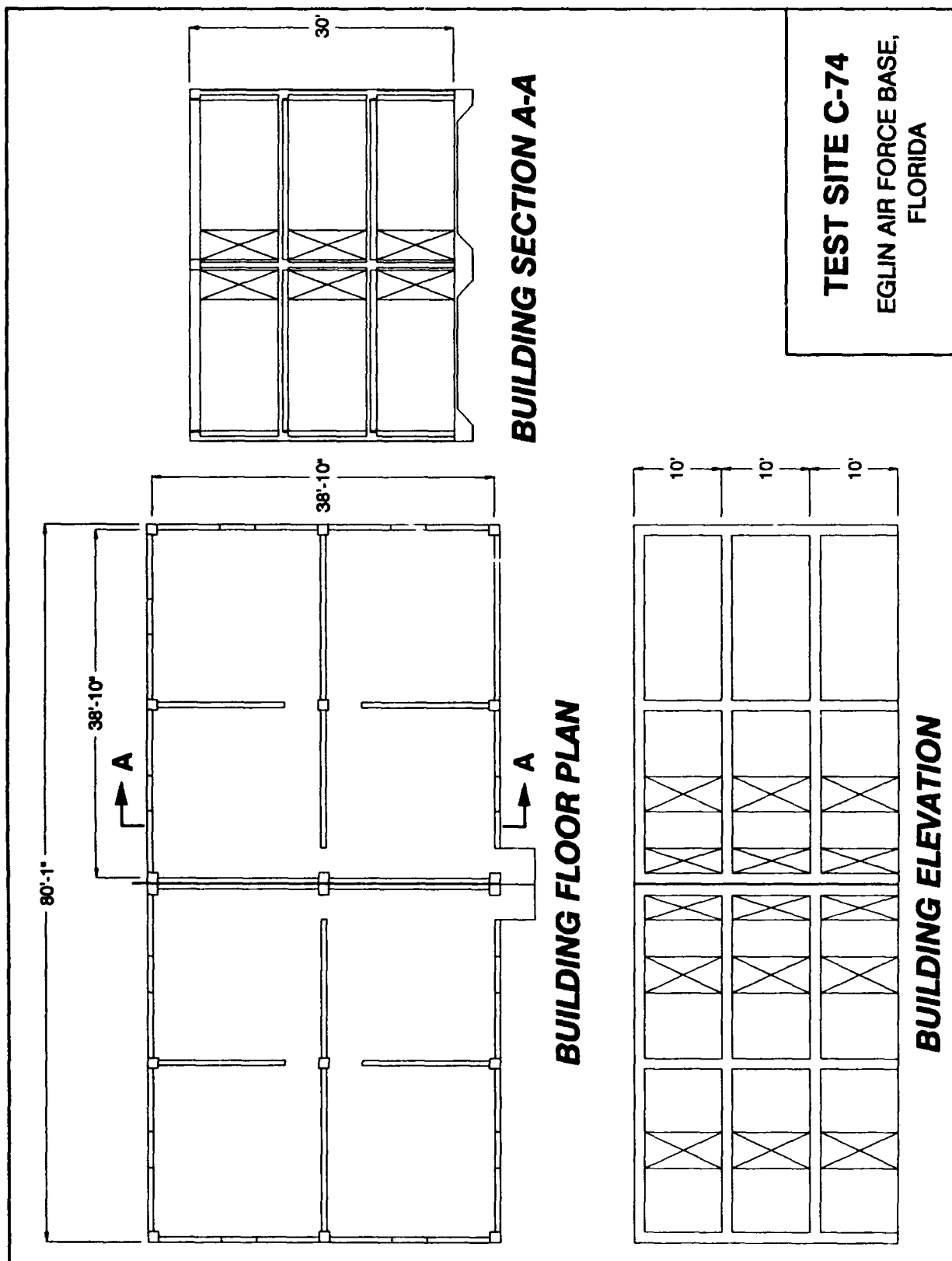


Figure 31. Design Plans of Undamaged Cast-In-Place Building Vulnerability Test Target (C-74 Test Site, Eglin Air Force Base, Florida).

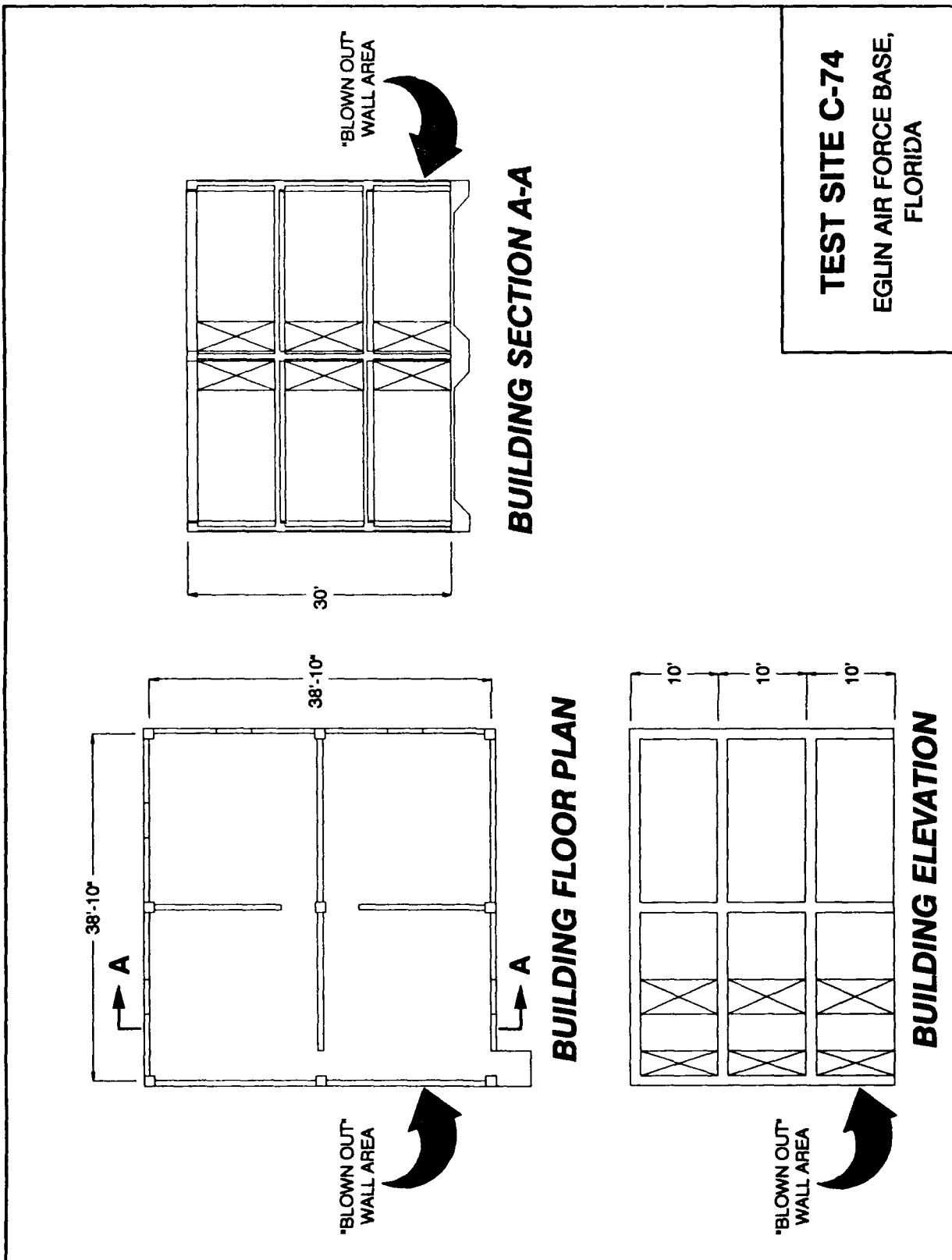


Figure 32. Design Plans of Damaged Cast-In-Place Building Vulnerability Test Target (C-74 Test Site, Eglin Air Force Base, Florida).

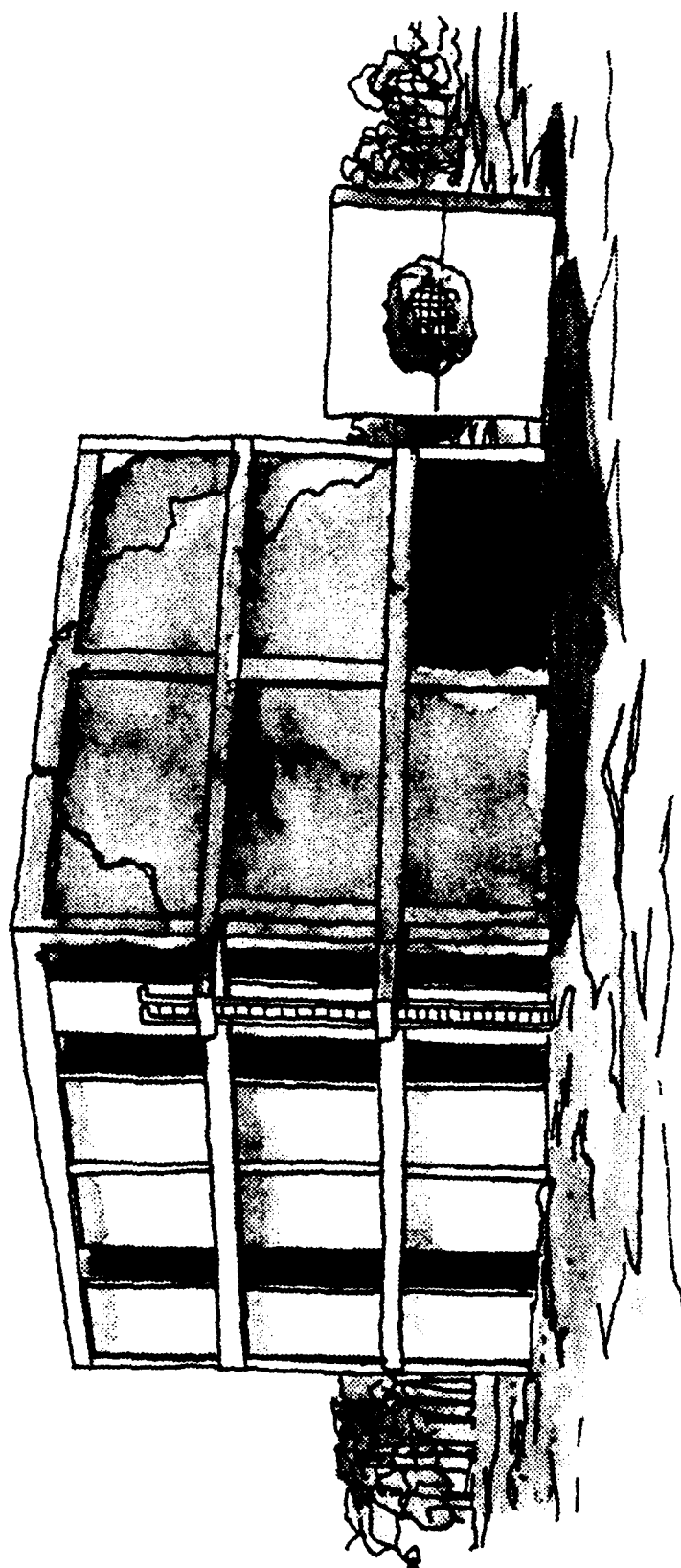


Figure 33. Sketch of the Cast-In-Place Building Vulnerability Test Target (C-74 Test Site, Eglin Air Force Base, Florida)

has a significant breach. In addition, on the north side of the building are several unfinished doorways. While these openings are not actually the result of bomb damage, they can be advantageously used, to compare different shotcrete strategies with the elimination of the variable of localized degree of cracking.

C. EXPEDIENT REPAIR STRATEGIES

1. General Strategies

A four-by-two matrix of strategies is recommended, representing four general methods using two different shotcrete materials. The two materials recommended are a standard dry-mix process shotcrete using an accelerating admixture and a similar mixture which incorporates steel fibers. The strategies are illustrated in Figures 34-41. Each of these figures shows pictorial illustrations of both an actual repair in progress and a research test of the strategy in progress. The research test, in this case, could be either the doorway openings on the cast-in-place building vulnerability test target (C-74 Test Site) or a frame used for panel tests. Figures 34 and 35 illustrate a "simple" repair strategy, using plywood as a backing material and filling the breach with the shotcrete material without additional reinforcement. An advantage of this method is the simplicity of construction. A disadvantage is a possible reduction in tensile/flexural strength. The use of steel-fiber reinforcement may overcome this potential disadvantage. Figures 36 and 37 illustrate a similar method (plywood backing), but with the addition of wire mesh reinforcement. An advantage of this method is the potential for increased tensile/flexural strength. A disadvantage is that the application of shotcrete must be done in two lifts, with the mesh inserted manually between lifts. Figures 38 and 39 show another similar method, which uses retrofitted reinforcing steel "rebars". An advantage of this method is a potentially very rigid system with excellent structural capabilities. A disadvantage is the manual labor which would be required to insert retrofit rebars (this may be particularly difficult in the postattack environment). Another disadvantage is the potential for segregation (sand pockets) behind the steel bars. Figures 40 and 41 illustrate a potentially attractive repair strategy, because entry into the building is not required before the repair.

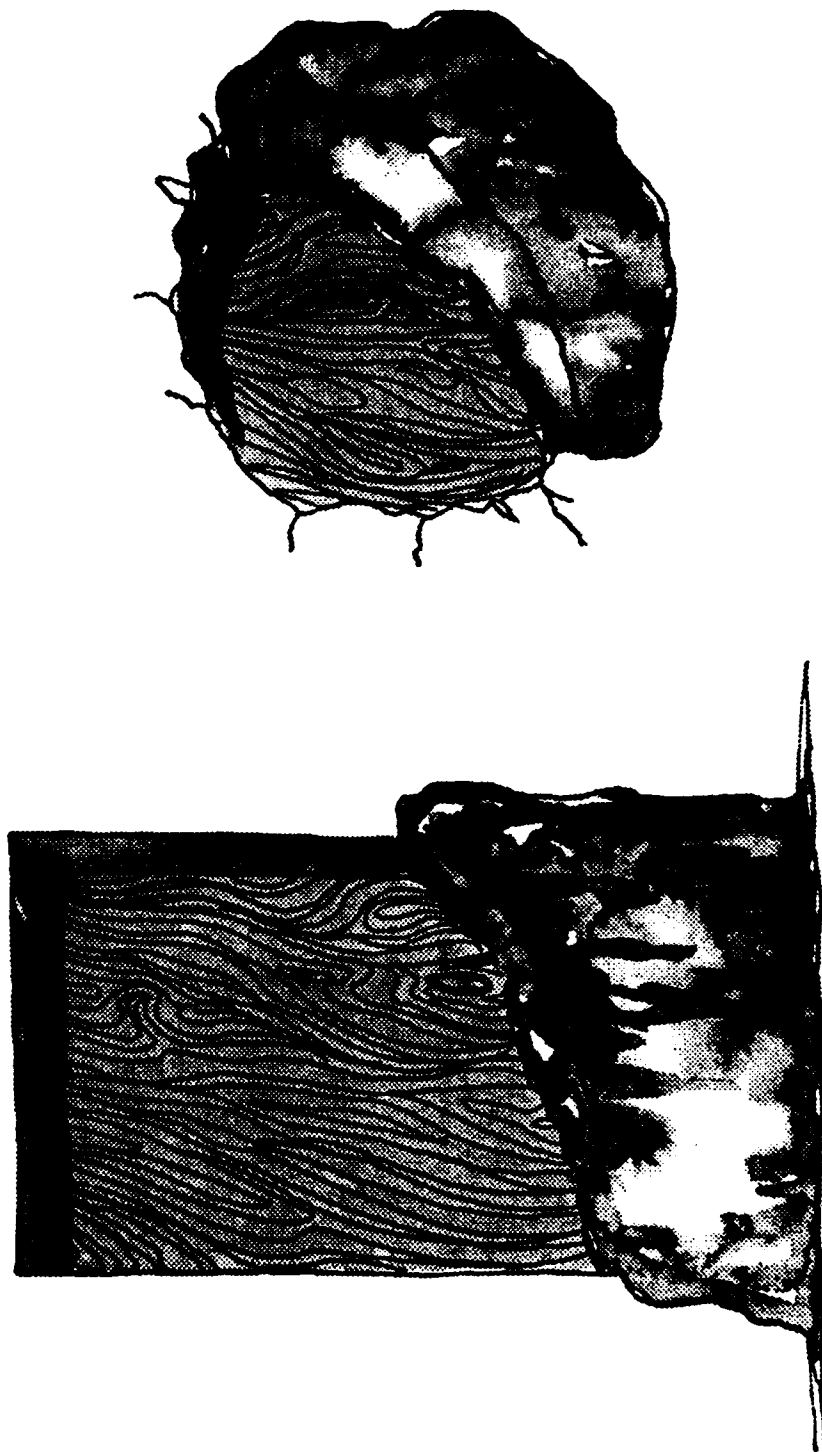


Figure 34. Repair Strategy: Wood Backing with Standard Shotcrete.

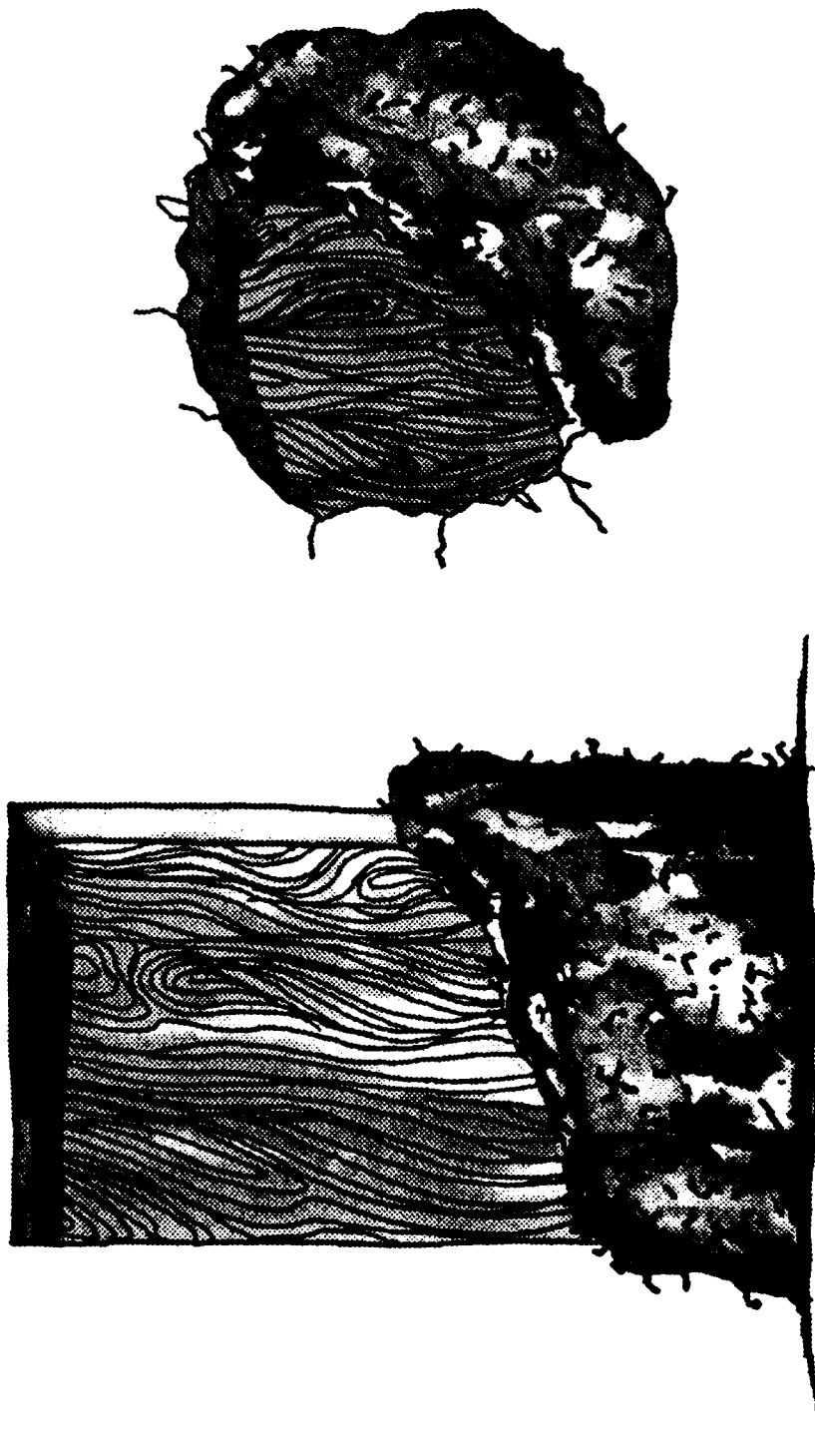


Figure 35. Repair Strategy: Wood Backing with Fiber-reinforced Shotcrete.

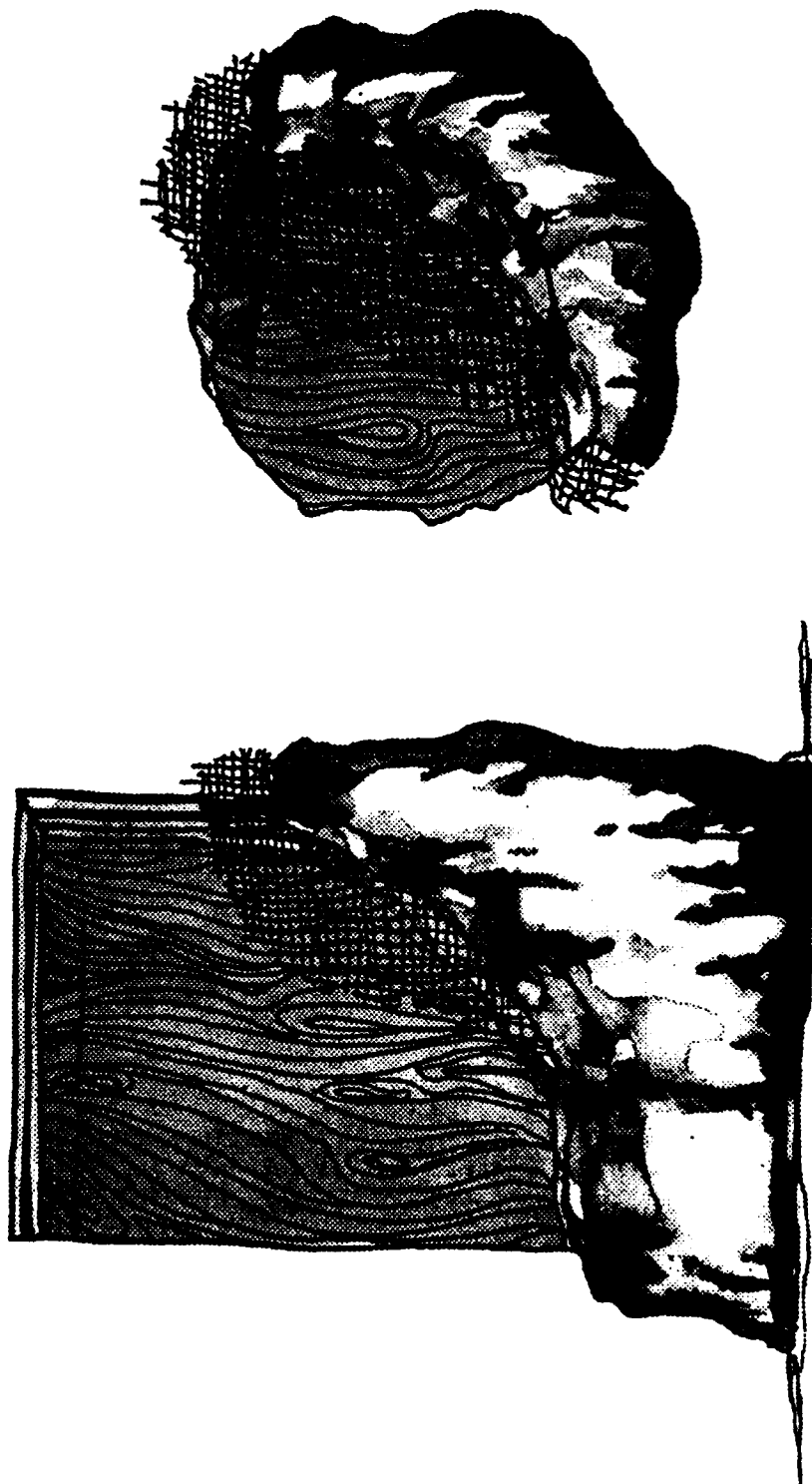


Figure 36. Repair Strategy: Wood Backing, Mesh, Standard Shotcrete.

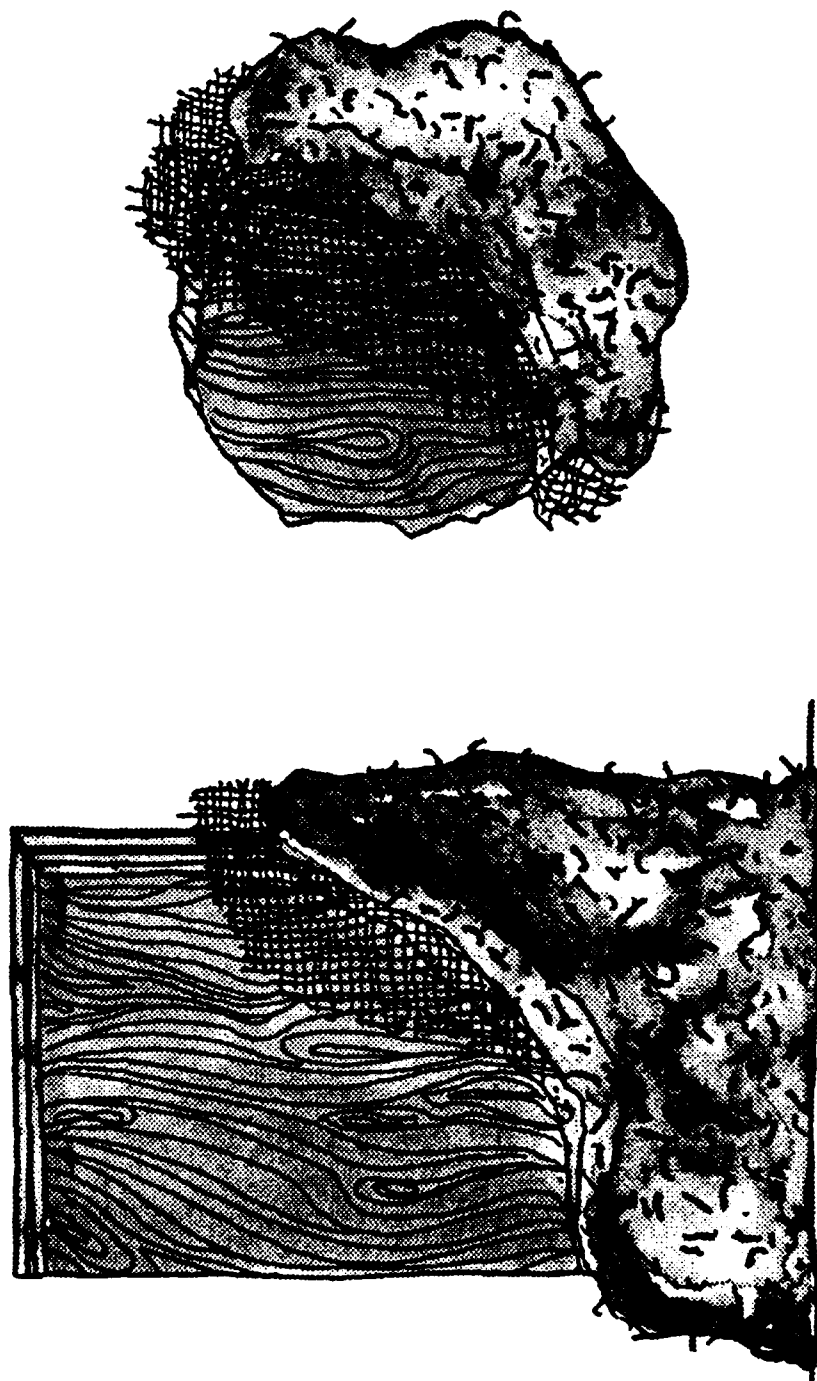


Figure 37. Repair Strategy: Wood Backing, Mesh, Fiber-reinforced Shotcrete.

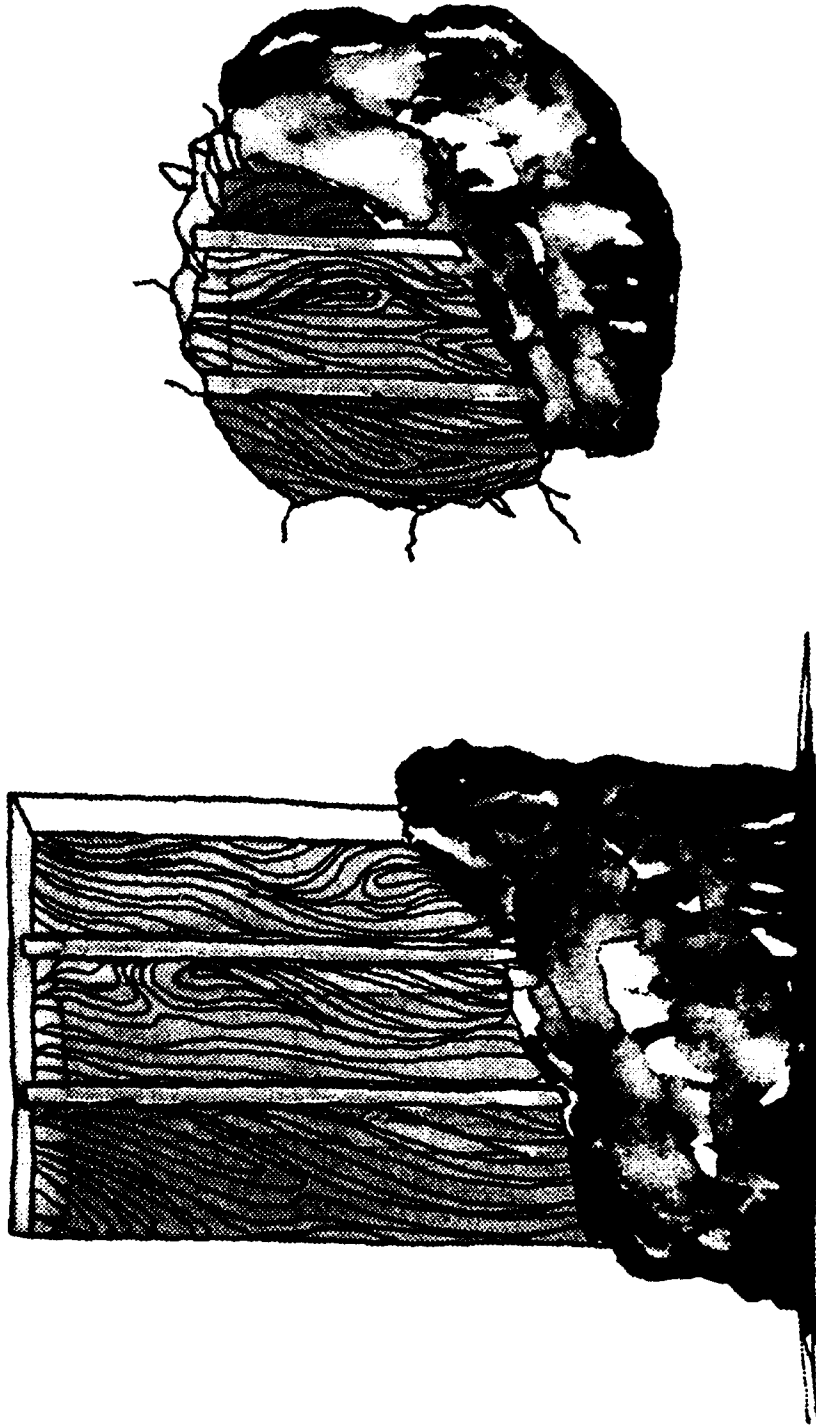


Figure 38. Repair Strategy: Wood Backing, Retrofit Rebar, Standard Shotcrete.

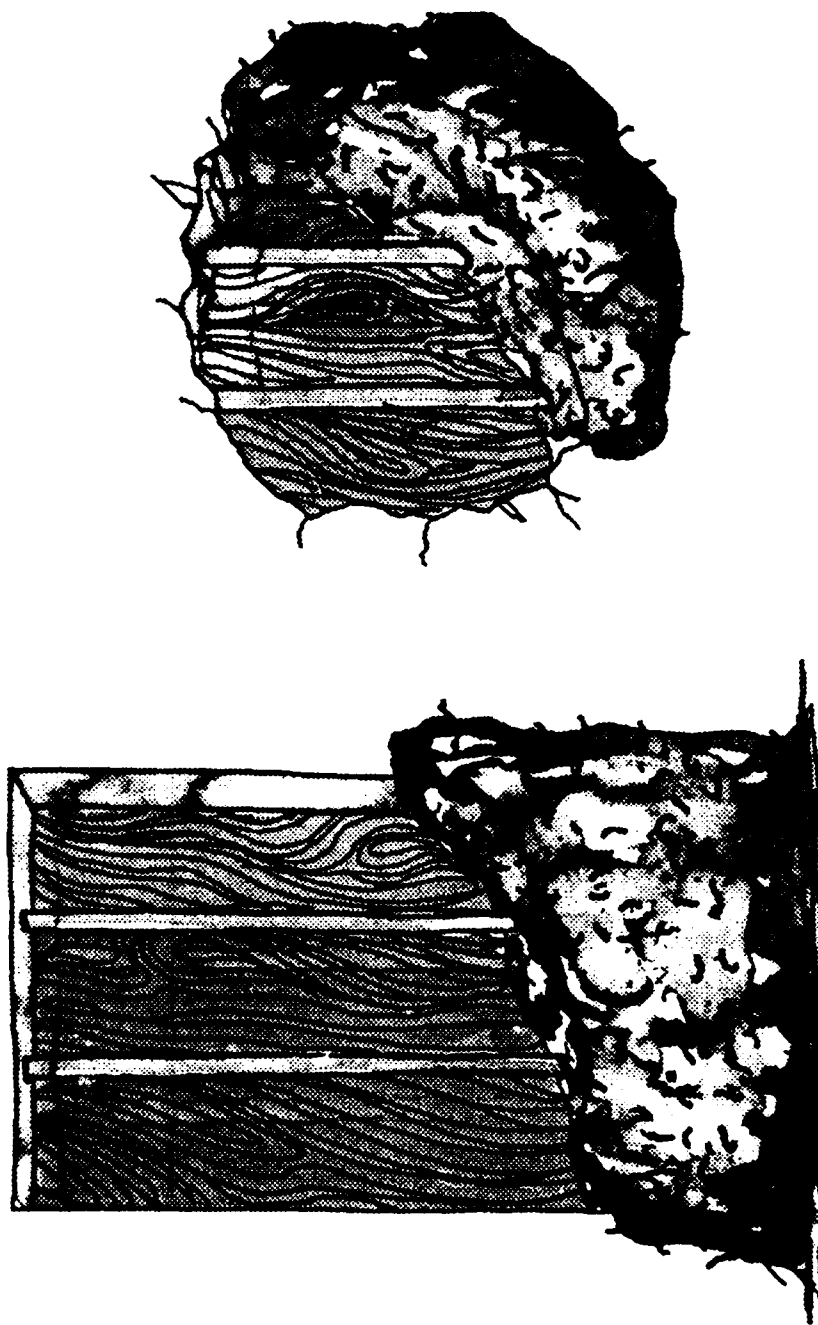


Figure 39. Repair Strategy: Wood Backing, Retrofit Rebar, Fiber-reinforced Shotcrete.

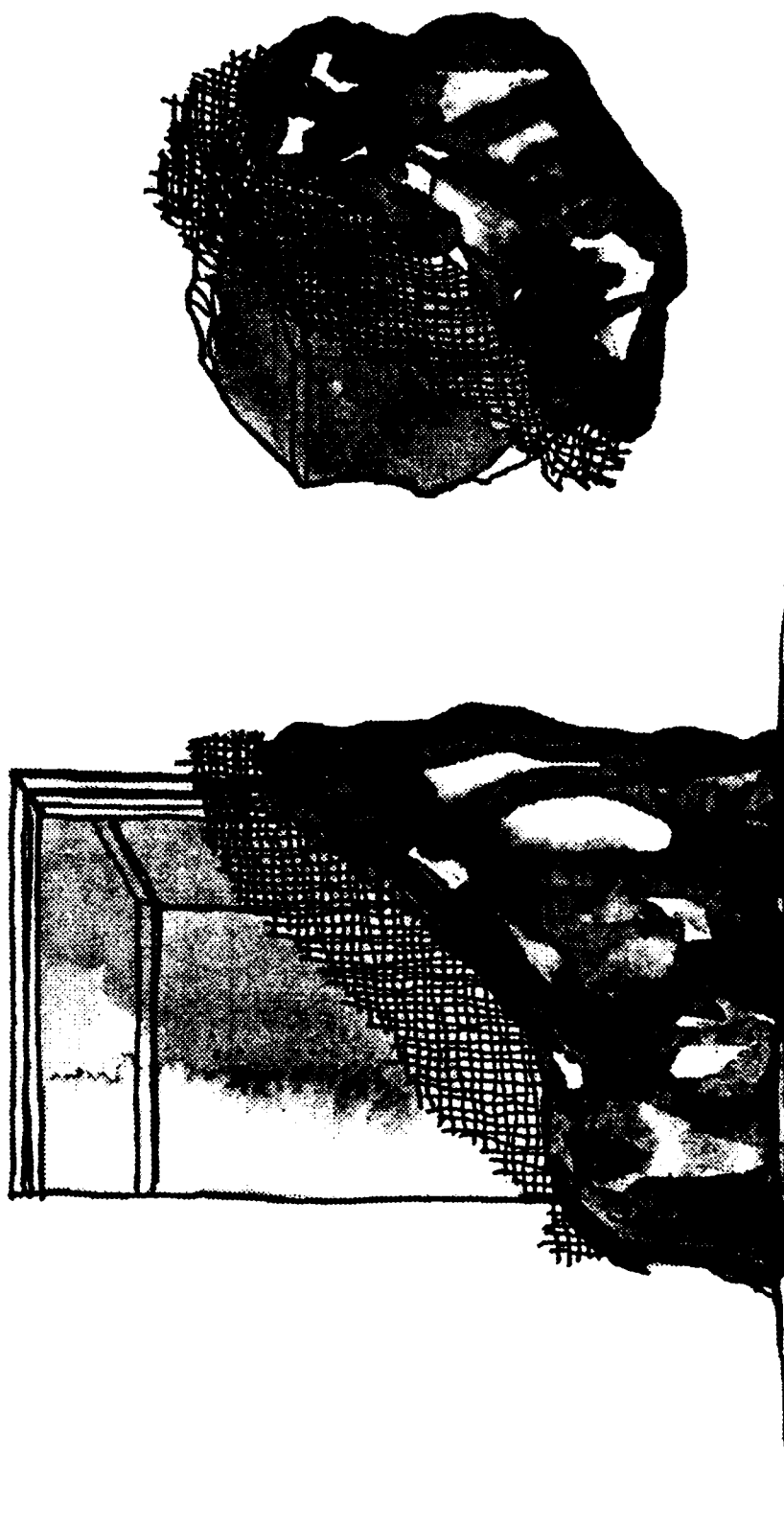


Figure 40. Repair Strategy: Mesh Backing, Standard Shotcrete.

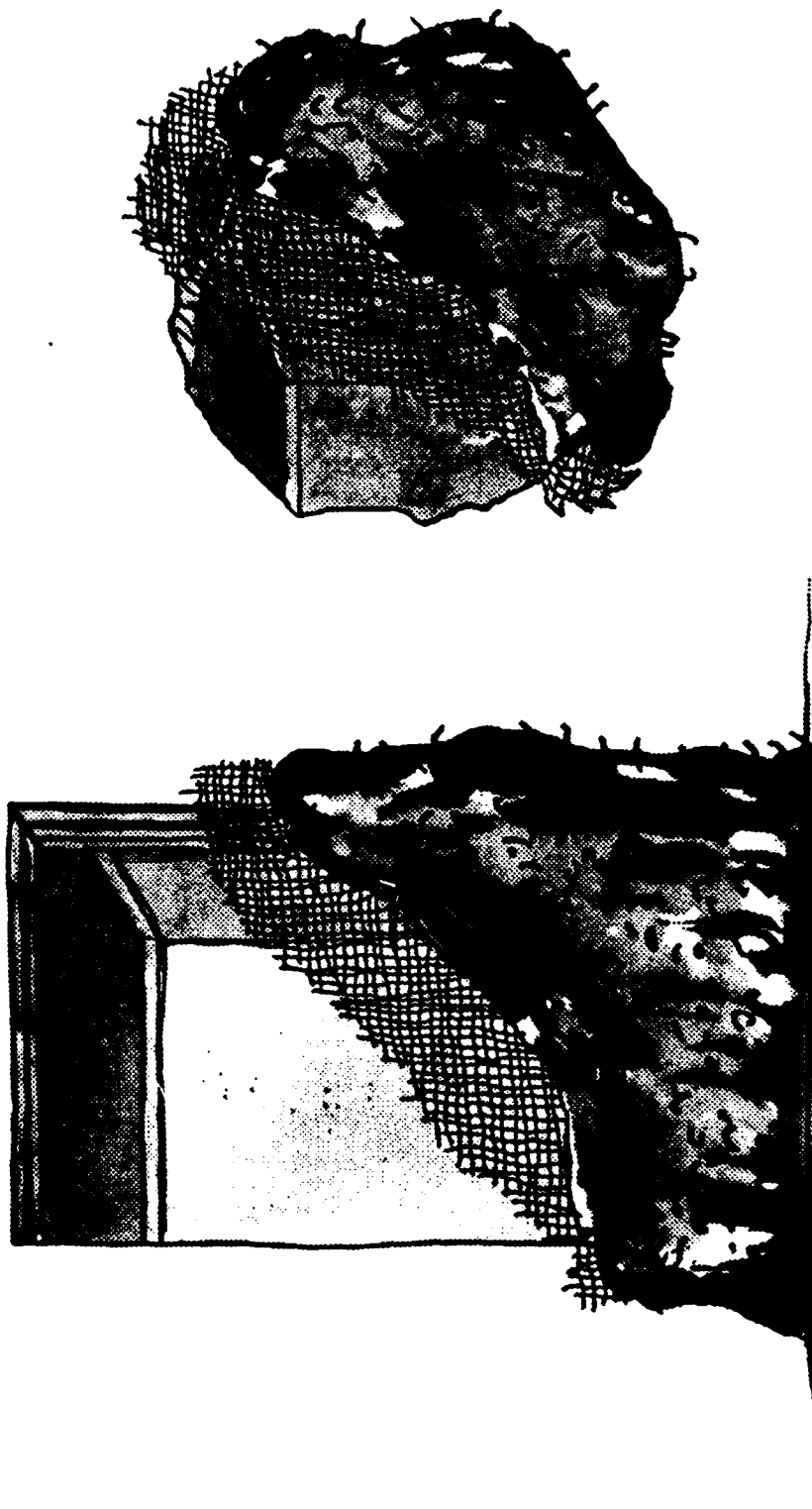


Figure 41. Repair Strategy: Mesh Backing, Fiber-reinforced Shotcrete.

In this strategy, a mesh backing is fitted from the outside of the structure and contoured as closely as possible to the damaged area. As previously mentioned, the major advantage of this method is the potential for repair without entry. This could potentially save time, but more importantly, could improve safety before building reentry by critical personnel. The disadvantage of this method is that some concrete spray will pass through the wire mesh (which could have a detrimental effect on mission-critical equipment contained within the building).

2. Field Application Test Strategies

Each of the repair strategies previously discussed should be evaluated by field testing. These tests would include, at a minimum, a series of large-scale panel tests using each of the repair strategies. At least 5 panels for each strategy are recommended, to be used for: (1) material tests for very early (about 8 hours) strength evaluation, (2) material tests for early (about 24 hours) strength evaluation, (3) material tests for ultimate (28 days) strength evaluation, and (4) repair evaluation by laboratory and/or field testing (described in a subsequent section). An additional series of *in situ* tests on the doorway openings on the cast-in-place building vulnerability test target (C-74 Test Site) is recommended. These tests will give information about the ability of crews to perform repairs under field conditions and will allow large-scale *in situ* evaluations of the repair strategies. Based on the initial field tests, a strategy can be chosen for an expedient wall repair using shotcrete. The "blown out" wall on the cast-in-place building vulnerability test target (C-74 Test Site) is recommended for such a test. If project planning requires that a strategy for wall replacement be chosen in advance, the recommended choice is the strategy illustrated in Figure 39, with retrofitted rebars and steel-fiber-reinforced shotcrete. An additional test which could be performed easily is the repair of the breach on the (previously tested) penetration slab located adjacent to the cast-in-place building vulnerability test target (C-74 Test Site). The purpose of this test would be to determine the difficulty in achieving a good repair when a high density of reinforcing steel is present. Coring of the repaired breach would be used to determine the effectiveness of the repair.

3. Evaluation of Repair Strategies

Evaluation of repair strategies must address two major concerns, the quality of the shotcrete material in-place and the quality/suitability of the overall repair. Evaluation of the in-place material quality involves sampling and testing for such properties as compressive strength and flexural strength. In addition, the specimens will allow subjective judgements to be made about lamination, segregation, or other detrimental properties of the shotcrete.

Determination of the quality/suitability of the overall repairs is more difficult than the evaluation of material properties. Large-scale *in situ* testing is preferred. This testing could be done by a large-scale explosive test, so that a planar air blast would strike the building. This type of test can compare the strategies to each other, and to the existing (remaining) structure. The disadvantage of this type of test is the high degree of planning and precautions which must always be included in aboveground explosive tests. A smaller scale explosive testing program might be just as useful. A shielded grenade blast (such devices are used by antiterrorist teams to make forced entries) could be used to evaluate the performance of both the repair strategies and of the existing structure. Penetration tests could also be used, using either a penetrating weapon, a hydraulic ram, or a crane mounted "wrecking ball." Each of these large-scale *in situ* tests has advantages, but each requires specialized equipment and procedures. The choice of which, if any, of these tests can be performed must be based on the availability of equipment and support.

Panel tests offer a supplement (or an alternative) to large-scale *in situ* tests. The disadvantage of panel tests for evaluating repair strategies is that they only offer a relative comparison, since they do not address the existing structure. Panel testing can be done in the laboratory using a large loading frame. Such tests have been described in detail by numerous authors (e.g., Reference 29). An attractive alternative is the use of the Antipenetration Laboratory at the SKY-X Test Site, Tyndall Air Force Base, Florida. This facility, illustrated in Figure 42, could be used to realistically compare the capability of the shotcrete repairs to resist subsequent penetration. It must be noted, however, that results would be relative and not absolute, since the repairs (panels) would not have the

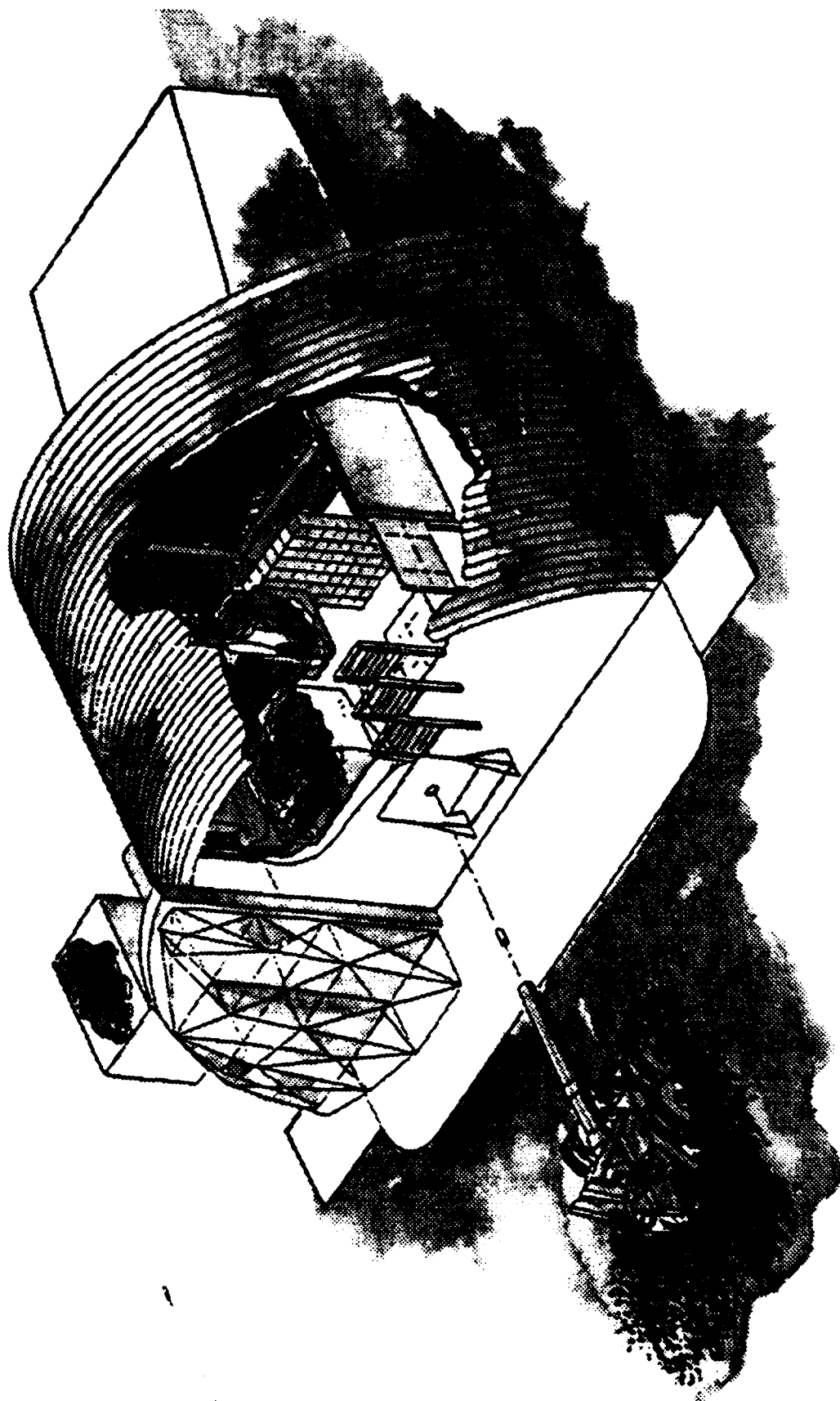


Figure 42. Sketch of the Antipenetration Laboratory at the SKY-X Test Site (Tyndall Air Force Base, Florida).

confinement which would occur in a real structural repair (i.e., the edges would be free rather than fixed).

D. TRAINING PROGRAM

A comprehensive training program was researched by Valencia (Reference 8), in which all supervisory personnel, potential shotcrete crews, and associated persons were participants. The course content was presented and demonstrated by selected individuals recognized as knowledgeable and experienced in their respective fields of shotcrete technology. In addition, they were persons who could interpret and explain particular specifications and requirements important to shotcrete application. In the training program, construction personnel experienced in general construction practices, but not in the use of shotcrete, were given a 2-day training course before a test series. In the test series, all of the crews were able to meet or exceed design parameters. Use of a training program similar to that described herein is recommended if a crew which is not "experienced" is used in the shotcrete application process.

One of the key components of the successful training program reported by Valencia (Reference 8) was a separate training schedule for crew members and supervisors. The training for crew members emphasized practical training with the shotcrete equipment and field training to learn application techniques. However, before any field training, an introductory classroom session was given which emphasized general principles and objectives. This initial instruction was considered an essential component in the preparation of the crew members for field training and was credited with dispelling the initial apprehension often displayed by prospective shotcrete crew members. An additional benefit noted was an increased level of overall interest in product quality by crew members. The supervisor training emphasized principles of design, application, and quality control. The increased level of classroom training made supervisors more aware of the "big picture" and more able to handle day-to-day problems. The classroom training included instruction on such important topics as planning, logistics, and crew coordination. On the second day, the supervisors gained practical experience by rotating in as shotcrete crew members.

Figure 43 describes a training course which is based on the course reported by Valencia (Reference 8). Although changes have been made where appropriate, the general objectives are the same:

- 1) To introduce personnel to fundamental shotcrete practice.
- 2) To give some indications of problems which have arisen with shotcrete applications in other major projects.
- 3) To provide prerepair experience, working and maintaining the shotcrete machine and auxiliary equipment.
- 4) To gain an understanding of the importance of consistently achieving high standards of quality control.
- 5) To evaluate candidates by means of practical and written tests for the purpose of qualification within the program.

SUPERVISORY PERSONNEL - CLASSROOM (DAY 1)

Orientation and Course Objectives

Objectives for shotcrete use in expedient repair

Aggregate evaluation for suitability

Cement composition, types and behavior

Accelerators, general composition use and selection precautions

Methods of evaluating quality of shotcrete

a) Laboratory evaluation

b) In-place evaluation

Operating principles of shotcrete equipment

a) shotcrete machine

b) Batching equipment

Planning and logistics of shotcrete operations

Interpretation of specifications

Placement techniques

Application principles

Crew coordination

Placement of shotcrete on test panels for qualification of mix-design

Testing of shotcreted panels

Evaluation of placed shotcrete

EVALUATION

Figure 43. Shotcrete Technology Course for Expedient Repair.

SUPERVISORY PERSONNEL - LABORATORY (DAY 2, MORNING)

Demonstration/discussion of mix design principles, including:

- 1) General mix design practice
- 2) Design of cement/admixture combination
 - a) Setting times
 - b) Strength

Demonstration/discussion of evaluation principles, including:

- 1) General evaluation practice
- 2) Strength testing (compressive, flexural, tensile)
- 3) Other evaluation techniques (pullout test, rebound hammer, etc.)
- 4) Sawing of test specimens from panels
- 5) Large-scale testing of panels

SUPERVISORY PERSONNEL - FIELD TRAINING (DAY 2, AFTERNOON)

Set-up and familiarization with shotcrete equipment:

- 1) Shotcrete machine
- 2) Batching equipment
- 3) Compressor
- 4) Water line
- 5) Admixture feed system

Calibration of shotcrete equipment

- 1) Sand-feed system
- 2) Aggregate-feed system
- 3) Cement-feed system
- 4) Mixing apparatus
- 5) Admixture-feed system

Trial batch of shotcrete

Participation as crew member, including operating gun and nozzle

FINAL EXAMINATION

Evaluation by students including comments and suggestions for improvement

Figure 43. Shotcrete Technology Course for Expedient Repair (continued).

SHOTCRETING CREW - CLASSROOM (DAY 1, MORNING)

Course objectives and orientation

- a) What shotcrete is and what it can be used for
- b) Why shotcrete would be used for expedient repair

Explanation of tests to be performed

Accelerators - When and why are they used?

Safety Requirements for Shotcreting

SHOTCRETING CREW - FIELD WORKSHOP (DAY 1, AFTERNOON)

Operating principles of Shotcreting equipment

Set-up and familiarization with shotcrete equipment:

- 1) Shotcrete machine
- 2) Batching equipment
- 3) Compressor
- 4) Water line
- 5) Admixture feed system

Calibration of:

- 1) Sand-feed system
- 2) Aggregate-feed system
- 3) Cement-feed system
- 4) Mixing apparatus
- 5) Admixture-feed system

Trial run of equipment:

- 1) Adjustment of air and water
- 2) Moisture adjustment of mix

Equipment maintenance and cleanup

Figure 43. Shotcrete Technology Course for Expedient Repair (continued).

SHOTCRETING CREW - FIELD TRAINING (DAY 2, MORNING)

Review of previous days work

Discussion of shotcrete placement techniques

Selection of crews (three individuals per crew)

Preparation of equipment for days work

Demonstration of shotcrete placement techniques:

- 1) Vertical panel
- 2) Horizontal panel

Demonstration of shotcrete application

- 1) Application of shotcrete to wet surface
- 2) Preparation of previously shotcreted surface for another lift

Preparation of test panels by crew members as time allows

SHOTCRETING CREW - FIELD TRAINING (DAY 2, AFTERNOON)

Participation with supervisory personnel

- 1) Familiarization, including set-up and calibration procedures
- 2) Preparation of test panels, supervisors acting as crew members

Continued preparation of test panels, with crew members switching jobs

Equipment maintenance and cleanup

Figure 43. Shotcrete Technology Course for Expedient Repair (concluded).

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL

Shotcrete is a material which appears ideal for expedient structural repair. A primary advantage is the potential for use of locally available materials commonly used for Portland cement concrete, rather than having a stockpile of material ear-marked for expedient repair. In general, shotcrete can provide rapid repairs for structural and sealing protection in a postattack environment. Automated equipment is available which allows shotcrete to be used in remote areas. These self-contained units carry their own materials, water supply, and pumping capability. This is a primary concern in a postattack environment, where utilities (water, electricity, etc.) may be unavailable. Shotcrete, particularly when used with steel fibers, is very resistant to tensile/flexural failure and penetration. It is concluded by the author that shotcrete can be used as an expedient replacement for any proposed (cast-in-place) conventional concrete repair. A systematic program of research on the use of shotcrete for expedient repairs is recommended.

B. RECOMMENDATIONS FOR PROPOSED FIELD TEST

A testing program with a matrix of strategies has been described for the evaluation of the quality and suitability of shotcrete for expedient structural repairs. Evaluation of material quality was discussed, as well as the evaluation of the overall repairs. Large-scale *in situ* testing was presented as the preferred alternative for evaluation of the overall repairs, with panel tests presented as a supplement (or alternative) to the large-scale *in situ* tests. A training program was presented in the event that an inexperienced shotcrete crew was utilized.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

There are various needs for future research in the use of shotcrete for expedient repairs. Some of the needed research deals with materials, some with application techniques, some with automated equipment, and some with personnel. Some research recommendations related to material properties include: (1) development of improved design criteria and specifications, (2) investigation of types of reinforcement, such as welded wire vs chain-link fabric, and optimum opening size, (3) determination of long-term effects of accelerators on material properties, (4) determination of factors which affect accelerator/cement compatibility, (5) determination of factors which affect the relationship of early strength versus ultimate strength and ways to increase the dosage of accelerators without reducing ultimate strength, (6) determination of the properties and durability of steel-fiber-reinforced shotcrete under blast and penetration loads, as well as under adverse environmental conditions, and (7) determination of the threshold level for airborne accelerator causticity and its long term effects. Some research recommendations related to application techniques include: (1) determination of the relationship of exit velocity of particles to ultimate properties of the shotcrete (could be done with a high-speed photography study), (2) development of improved shotcrete handling systems which require less space, (3) development of improved accelerator feeders, (4) determination of optimum nozzle configurations and water pressures for various configurations, (5) development of standard procedures for application of shotcrete under extreme environmental conditions, and (6) establishment of standard tests for rebound quantity, early strength, correct water/cement ratio, and bond strength. Recommended research on automated equipment includes the development of a system similar to the MASERV (Mobile Automated Shotcrete Expedient Repair Vehicle) concept presented herein. Recommended research on personnel would include: (1) determination of the capabilities of personnel equipped with environmental protection gear to apply shotcrete and (2) development of standard training procedures for potential crew members.

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Reading, T. J., "Durability of Shotcrete," *Concrete International, Design and Construction*, Volume 3, Number 1, January, 1981, pp. 27-33.

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Schutz, R. J., "Properties of Shotcrete Admixtures," *Proceedings, Shotcrete for Ground Support*, The Engineering Foundation Conference, Easton, Maryland, October 4-8, 1976, ACI Publication SP-54, The American Concrete Institute, Detroit, Michigan and The American Society of Civil Engineers, New York, New York, 1977, pp. 45-58.

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Webster, R. P. and Kukacka, L. E., "In Situ Repair of Deteriorated Concrete in Hydraulic Structures: Feasibility Studies," Technical Report REMR-CS-6, Process Sciences Division, Brookhaven National Laboratory, Upton, New York, for Structures Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, May, 1987. (ADA-182-297)

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APPENDIX A

SHOTCRETE BIBLIOGRAPHIC DATABASE ENTRIES

Appendix A contains a computerized printout of review comments from a bibliographic database. Appendix A is included to provide additional information to the interested reader and is printed herein exactly as received, without editorial correction. The appendix uses nonstandard margins and contains undefined abbreviations.

A partial list of abbreviations used in this appendix include the following: shotcrete (SC), compressive strength (CS), tensile strength (TS), water-to-cement ratio (W/C), length-to-diameter ratio (L/D), thickness (t), quality assurance (QA), quality control (QC), finite element method (FEM), Young's modulus of elasticity (E), new Austrian tunneling method (NATM), and United States Army Corps of Engineers (USACE).

REFBASE - BIBLIOGRAPHIC DATABASE - ARA GULF COAST DIVISION

TOPIC SUMMARY: Shotcrete References (SH)

Subtopic	Title	Number
1	Shotcrete General	20
2	Shotcrete Specifications	2
3	Shotcrete Evaluation / Engineering Properties	36
4	Shotcrete Repair / Rehabilitation / Structural	18
5	Shotcrete Equipment / Forming / Nozzling	16
6	Shotcrete in Tunnels / Ground Support	27
7	Shotcrete Payment Provisions	5
	Total References (SH)	124

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-001

AUTHOR(S): -0-

PAPER TITLE: The Shotcrete Process

DESCRIPTIVE TITLE NOTE: manufacturer's literature

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: -0-

CORPORATE AUTHOR OR PUBLISHER: International Gunite, Inc.,
Pittsburgh, Pennsylvania

MONITORING AGENCY: -0-

PUBLICATION DATE: 1988

PAGES (papers): -0-

TOTAL PAGES (books): 4

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This manufacturer's literature provides a good summary of
SC properties combined with some "rule-of-thumb"
guidelines for design and use.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-002

AUTHOR(S): -0-

PAPER TITLE: Guide to Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication 506R-85

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1985

PAGES (papers): -0- TOTAL PAGES (books): 41

DISCUSSION: -0-

KEYWORDS: equipment, mix proportioning, placing, quality control,
shotcrete

REVIEW: This ACI summary provides an excellent overview to SC.
Contents include summaries on general aspects, materials,
equipment, crew, procedures, proportioning and
preconstruction testing, batching and mixing, placement,
quality control, references, and payment provisions.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-003

AUTHOR(S): Reading, T. J.

PAPER TITLE: Shotcrete as a Construction Material

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 1-14

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Conventional concrete has the ability to be molded into any shape by placement in a form. SC has the added advantage of using only a backup surface as a light form, or even no form. SC is well adapted for thin, lightly reinforced sections in new construction. Common uses include roofs, walls, canal linings, tunnel linings, swimming pools, prestressed tanks, thin overlays over structural materials, repair of concrete deteriorated by fire or earthquake, rock slope stabilization, and refractory linings for fireproofing. SC is not usually recommended for heavy sections, due to the relatively low placement rate (1 to 8 cubic yards per hour per gun). Thin overlays for rehabilitation may have bonding

difficulties over time, particularly in cold climates. Removal of loose material prior to SC placement is essential. Use of a liberal application of SC ($t > 1.5$ inches) and wire mesh is recommended. "Hydration at the nozzle" is a common term describing the addition of mix water at the nozzle for the dry-mix process. Actual hydration continues over a period of years. Rebound may cause the mix to be too rich and should be minimized. Most reliable data indicate that the W/C ratio in good field SC is in the range of 4 to 5.5 gallons per sack (0.35 to 0.50 by weight). SC has similar properties as a conventional concrete with the same mix proportions. The major advantage of SC is the convenience of application and the high bonding which can be achieved. Equipment is available to gun SC with larger aggregate (up to 1 inch), but there are disadvantages, particularly in the increased rebound. Testing of SC should be done by taking cores from the structure or from a test panel shot in the field. The SC inspector should systematically sound each layer in the structure to test for "drumminess." Based on a ACI Committee 506 questionnaire, the following has been found: (1) use on this continent has included repair of buildings and chimneys as well as hydraulic structures, (2) thick sections, especially when highly reinforced, increase the danger of trapping excessive rebound, (3) SC is noted for its high bonding, (4) some complaints of cracking in long continuous walls, (5) some questioned the corrosion resistance, (6) fair record in hydraulic structures under severe conditions, (7) frequent repair with thin SC may be a cost-effective repair solution, (8) common causes of failure cited include: (a) bonding failure - usually due to poor preparation, (b) sagging (sloughing) of SC during application, and (c) inclusion of trapped rebound, (9) less common causes of failure include: (a) applications too thin, (b) improper design or placement of reinforcing, and (c) insufficient wet curing, (10) uncommon causes of failure include: (a) poor materials, (b) mix too rich, (c) mix too lean, (d) nonuniform feed causing inconsistent mix, (e) water not intimately mixed, (f) too much finishing, (g) rough surface texture, (h) inadequate equipment such as compressor capacity, (i) suspected porous SC, (11) one firm stated that the cause of poor SC is inexperienced designers, contractors, and inspectors, (12) strength tests are variable and

usually high unless there are rebound lenses or pockets,
(13) cost is in the range of \$60 to \$150 per cubic yard
and is usually economical for cases where the thickness
is up to 3 inches.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-004

AUTHOR(S): Crom, T. R.

PAPER TITLE: Dry-Mix Shotcrete Practice

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 15-32

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: There has been an increase in the manufacturers of SC equipment, with several listed in the paper. The minimum equipment for a SC operation is the gun, an air compressor, material hose, air and water hoses, nozzle, and sometimes a water pump. There is a standard pattern for most SC operations. First, the materials must be batched, usually in quantities of about 94 lb of cement to 400 lb of sand. The mixed material is carried in suspension by air to the nozzle. Water is injected at the nozzle and mixing is completed at impact. A sand heater is needed if sand is very wet and is also useful in very cold climates. The two main types of guns are a double-chamber gun and a single-chamber gun. The

double-chamber gun lets material drop from the upper chamber into the lower (feed) chamber. The single-chamber gun acts something like a pistol with a revolving cylinder. Types I, II, and III cements have been used, with Type I most common. A normal SC sand has fineness modulus of about 2.5. Special aggregates may be used. Admixtures may be included in the mix water. SC may be shot against forms less stable than for concrete work. SC may be shot against the softest type of insulation material without serious damage to or compaction of the soft material. A good crew is needed for SC application. The following are necessary: (1) smooth flow of material, (2) sufficient water supply and pressure, (3) sufficient nozzle velocity, and (4) proper positioning and mobility of the nozzle operator. Sand pockets are a serious problem for SC. To reduce sand pocketing, many contractors use an air blowpipe to remove accumulated rebound. The nozzle is typically 6-10 feet from the surface. For reinforcing bar or wire encasement, the nozzle should be as close as practical. The nozzle should be at 90 degrees from the surface. SC cannot be used to fill small diameter holes or test cylinders, because the compressed air will create turbulence if not allowed to escape. The angle of the nozzle must be varied to insure encasement of reinforcement. Shooting rates of 25 to 60 bags of cement in 1:4 to 1:5 mix per hour are possible. Bond efficiency is usually very high (near 100%) if the shooting surface is cleaned before shooting. SC can dry quickly, so early and good curing is very important. Surface finish may be varied from a rough to a fine texture. Weather can be a problem. Excessive winds tend to segregate cement and sand. Rain may cause heavy visible damage by washing away or streaking the SC. Penetration of moisture can cause internal cracking and separation, particularly around reinforcement. Hot weather poses little problems for SC application, although early and adequate curing must be provided. Special precautions must be taken for use of SC in cold weather. Freezing of the fresh mix can be destructive and frost on the surface can prevent bonding. QC is usually done with CS specimens. One method uses a 4 inch diameter, 5 inch high cylinder shot against a 1/2 inch wire cloth and trimmed. Another method uses samples cut from test panels, which indicate not only the quality of the mix but also the quality of

the nozzle operator. The only true QA testing is to take cores from the structure.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-005

AUTHOR(S): Hoffmeyer, T. A.

PAPER TITLE: Wet-Mix Shotcrete Practice

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 59-74

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Wet-mix SC has much more control over mix proportions, often limiting rebound and dust production. Wet-mix SC can have up to 40% coarse aggregate and can be gunned in a zero slump mix with up to 3/4 inch aggregate. There are two main types of guns for wet-mix SC, positive displacement and pneumatic feed. The positive displacement gun pumps fresh concrete hydraulically to the nozzle, where an air ring injects compressed air to break up and spray the material. These piston pumps usually require a more plastic mix than for the pneumatic guns. The velocity of impact is reduced, often reducing the level of compaction. Delivery rates range from 1.5 to 12 cubic yards per hour. The pneumatic feed SC gun

uses slugs of material and slugs of compressed air to transport the material to the nozzle, where additional compressed air is used to create a high velocity impact. The lengths of the air slugs may be increased to reduce the weight per linear foot of hose and also to further increase the delivery velocity. The mixer operator has a greater responsibility in wet-mix SC for the correct mix proportions, potentially freeing the nozzle operator to concentrate on placement. Use of a blowpipe to remove rebound, especially in coarse aggregate mixes is very important. Preconstruction mock-up tests are highly recommended, with a case history given as an example. "Perfect" bonding can be achieved by first using the delivery system to wet sandblast the surface, then applying a high velocity air-water jet, and then gunning the wet-mix SC. Cost comparisons for the case study showed that the cost was greater than conventional for a 12 inch thick wall but much less than conventional for a 4 inch thick wall. A physical property comparison showed almost identical properties for a conventional concrete with similar mix proportions. Wet-mix gunning of low slump SC with lightweight aggregate has been a problem, with material sometimes "freezing" and plugging the pipe. The pumpability of the mix must be controlled by attention to the gradation and mix proportions. When weight is not critical, addition of sand can improve the pumpability.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-006

AUTHOR(S): Graham, J. R.

PAPER TITLE: Opening Remarks

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 1-2

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: No technical content in this paper. The proceedings of
the conference will be based only on written
contributions and no audio recordings will be made.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-007

AUTHOR(S): Mathews, A. A.

PAPER TITLE: Keynote Address

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 3-12

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This paper presented a historical perspective and general
overview of SC use with an emphasis on past successes and
problems. Having skilled and capable people at all
levels was stressed as essential for a successful
project.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-008

AUTHOR(S): Miner, G. M.

PAPER TITLE: Use of Shotcrete from the Standpoint of the Owner

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 13-17

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC (coarse aggregate "Gunite") was not used until the mid-50's. Introduced in this continent in 1967 in British Columbia. A case history is given for the use in the Hecla mines, which the author believes was the first use of SC in the US. The paper stressed the need for more research on SC, particularly in the equipment and techniques.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-009

AUTHOR(S): McClure, C. R.

PAPER TITLE: Use of Shotcrete from the Standpoint of the Designer

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 18-21

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case history is described where SC was used in a tunnel in Austria and Italy. The author was first against using SC, then became enthused. Another case history involved a tunnel in Canada which was having support problems. The tunnel was stabilized with SC by the contractor, even though he had no prior experience with SC. The author points out that the accumulation of design and performance data for SC projects would lead more designers to utilize SC for support.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-010

AUTHOR(S): Fox, K. H.

PAPER TITLE: Use of Shotcrete from the Standpoint of the
Contractor

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 22-28

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: "If it is handled properly it is one of the finest tools
we underground contractors have ever been given to aid us
in building tunnels." The author discussed mistakes made
in construction of the Tehachapi Tunnels. After a
cave-in in an area not supported by SC, the SC had
"relief" cracks for at least 75 feet away from the caved
area. This is the only time the author has seen cracks
in SC. He recommends the use of SC with mole equipment,

with 360 degree application directly behind the cutter head. He says not to trust SC with wire mesh reinforcing. Use steel rebars instead, because it is heavy enough to resist vibration and will result in good bonding.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-011

AUTHOR(S): Corns, C. F.

PAPER TITLE: Summary of Session I

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 29-32

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: No new material in this paper. Summaries of 4 papers
were included.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-012

AUTHOR(S): Bates, R. C.

PAPER TITLE: Shotcrete Safety and Environmental Control

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 130-142 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Health and safety problems are discussed, particularly dust, rebound, and causticity. Other longer term problems are lack of strength, residual causticity, and improper placement. Dust is a serious problem, with one measurement showing double the threshold limit. Dust protection for the crew is mandatory. Rebound can be dangerous, particularly if the crew is not outfitted with goggles. In addition, rebound can reduce visibility by coating goggles or face shields. A helper may wipe the

nozzle operator's goggles, replace them, spray water on them, or disposable plastic sheets may be used. Also, rebound combined with fog and dust may cause poor footing for the nozzle operator. Use of a boom to apply the SC is recommended wherever possible. Cement can attack the skin, and fast-set agents can cause serious chemical burns. A litmus paper test by the Bureau of Reclamation indicated that alkaline mist was penetrating the crew operators' respirators. Improved filters are available which eliminate this danger. Caustic substances can build up around collars, cuffs, watchbands, etc., and cleaning of clothing and personnel is essential for eliminating caustic burns. Protective creams are available to help prevent caustic burns. Dry-mix process can cause a build-up in static charge which could potentially ignite an explosive atmosphere. A frequent postshooting problem is the false sense of security that SC gives even before it has gained adequate strength to impede failures. Failures have occurred in fresh SC, and care should be exercised. Failures in older SC have been poorly documented, with poor bonding being a probable cause. Technicians who handled physical property samples complained of skin irritation, so that precautions should be taken similar to those of the SC crew. A serious problem is that water flowing through the SC area can develop a high-pH. Use of lime and alum can reduce the pH to allowable levels. Rebound material must be disposed of carefully for the same reasons, with common sense recommended. A wire-filled SC material can produce safety problems. The rebound from such material may penetrate protective gear, and exposed wires at the surface can cause lacerations. Surface coating should be considered for these materials. Discussion included comments that: (1) Europeans have developed some good tests for testing early SC strength (CS less than 200 psi), (2) tests by Bawa show that 4 hours time lapse is needed before SC is safe to work under, and (3) there is no data on worker claims from health related problems with SC.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-013

AUTHOR(S): Tibbs, H. E.

PAPER TITLE: Summary of Workshop A

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 143-152

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Discussion question and answers were included in this
section. Some of these have been incorporated into the
individual reviews.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-014

AUTHOR(S): Morris, J. W.

PAPER TITLE: Bureau of Reclamation Shotcrete Design Practices

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 153-159

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Tunnel design usually starts with a study of available geologic data. The type of excavation (machine, drilling, blasting, etc.) must be considered to determine the type and extent of support needed for the tunnel. Space limitations are critical in tunneling operations and must be considered in the design of ground support. Detailed studies and cost estimates must be employed to establish definite designs and specifications for a tunnel. The service for which the tunnel is intended

must be considered in the design. The QC of the SC must be considered. Conclusions about the economy/capability of combined steel rib/SC systems require more data. Additional thickness needed for a SC lined tunnel may increase the outer dimensions for removal and must be considered. Pictures are included which illustrate some instrumentation which has been used in tunnel work, including a Gloetzi pressure cell and a single position borehole extensometer.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-015

AUTHOR(S): Heuer, R. E.

PAPER TITLE: Selection/Design of Shotcrete for Temporary Support

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 160-174

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The first step is to identify the ground support problem requiring temporary support. There are 4 major classes of support problems: (1) surface deterioration, either by air slaking or by water softening, (2) loosening loads, (3) overstressing behavior, and (4) swelling ground. The use of SC usually is for one or more of 4 major functions: (1) to seal the surface, (2) to preserve ground strength, (3) for simple support of individual blocks, or (4) to act as a structural arch or ring.

Compatibility with ground behavior must be considered before selection of SC as a temporary support. SC has proven useful for ground exhibiting loosening behavior and also for problems with air slaking. SC may be useful for some cases of overstressed ground, but not for others. Practical considerations such as equipment compatibility, cleanup requirements, and cyclic time required for strength gain are important. Problems have been encountered with combination steel rib/SC systems, usually due to: (1) difficulty in developing good quality SC around and behind wood blocking installed with the ribs, (2) difficulty with overbreak requiring excessive volume of SC, and (3) difficulty developing adequate blocking between the ribs and the rock surface. SC was used to advantage in the Washington, DC Metro System. SC has been used in combination with tunneling machines (moles) with often poor results. Selection and/or design of SC temporary support is different for each type of support problem. For air slaking, the recommended rule of thumb is a nominal 2 inches of SC (with local minimum usually about 1/2 inch). To support loosening loads, the rules of thumb call for 2 inches of SC in good rock, 3 inches of SC in fair ground, 4 inches of SC in poor ground, and 5 inches in very poor ground. To support overstressed or swelling ground, the thrust predicted must be compared to the ultimate thrust capacity of the SC lining. The nominal thickness for these cases is usually the effective thickness plus 2 to 4 inches (safety factor).

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-016

AUTHOR(S): Cording, E. J.

PAPER TITLE: Geologic Considerations in Shotcrete Design

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 175-199

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Case study data is presented from the construction of the Washington, DC Metro System. Design of SC support must consider the interactions of the total support system. Careful observance of field performance is essential for evaluating the adequacy of SC. Specifications should be written in a flexible way to allow changes based on geologic conditions. Several design examples illustrate the combination of SC with other support mechanisms to create a stable system. Use of combined steel rib/SC

systems is best when the SC is used as blocking instead of timber. Fast-setting SC was useful as a permanent continuous lining. A thin SC lining over irregular rock surfaces is not adequate as the sole support in these cases: (1) drill and blast openings with diameter at least 20 feet, (2) zones where blocks 4 feet or more in width are bounded by smooth to slick joint surfaces and the overbreak is prominent, and (3) vertical side walls taller than 10 feet. A continuous thick SC arch can be analyzed as a concrete arch. A thin SC lining is controlled by: (1) thickness of SC, (2) frictional and bond strength at the rock-SC interface, (3) tensile properties of the SC, and (4) characteristics of rock blocks, including orientation, shape, size, bonding, and water pressures. Adequate thickness over protrusions must be applied even if large thicknesses have been placed in recesses of rock blocks. Bonding with slickensided or surfaces coated with clay gouge may be difficult or impossible. Tensile stress-strain properties of the SC will control the support capacity of the tunnel lining. The character of blocky rock should be investigated in the exploration stage, with important parameters including rock quality (RQD), orientation and condition of major joint sets and shear zones, location of major (particularly weak) structures, and determination of shear strength along joint surfaces. To obtain suitable information, core borings with less than 90% recovery are not acceptable.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 17

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-017

AUTHOR(S): Singh, M. M. and Bortz, S. A.

PAPER TITLE: Use of Special Cements in Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 200-231 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Since SC is not formed, it must have good adhesion.
Usually only 2-3 inches of thickness can be gunned in one
lift. For tunneling, the set time must be short to be
useful. Several combinations of accelerated and control
mixes of SC were evaluated, including both dry-mix and
wet-mix processes. Control mixes were Type III cement
without additives. Properties obtained included CS, FS,
shear strengths, secant modulus, tangent modulus,
Poisson's ratio, gas permeability, and shear and tensile

bond strength to coal, shale, and sandstone. Test panels of 6 inch thickness were produced with 3 lifts of 2 inches each. Several tests on smaller panels were completed before testing large panels (4x5.75 feet). The results of the testing program were presented in tabular and graphical form. It was concluded that the use of regulated set cement would increase the versatility of SC. This would require: (1) conveying the aggregate and cement separately and continuously mixing at the heading, (2) use of water heaters to heat the water, and (3) establishment of emergency dump and clean out procedures for work stoppages. Use of admixtures is an alternative, but toxicity and other factors need more investigation. If regulated set cement cannot be used, a Type III cement should be used instead of a Type I cement. More automation is needed to obtain more control over the spraying and the hydration of the SC.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-018

AUTHOR(S): Boileau, P. L.

PAPER TITLE: Summary of Workshop B

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 232-234

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: No new technical material here. This paper gives a very
brief summary of 4 papers presented in this session.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-019

AUTHOR(S): Hansen, K. D.

PAPER TITLE: Summary of Session X

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 436-440 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This paper contained summaries of 3 papers presented in this session. There was no new technical material here except for the following discussion which followed Mr. Graham's presentation on polymer SC. Discussion brought out that the unit material cost of polymer SC may be up to 4 or 5 times the unit cost of conventional concrete. However, when a systems approach to cost is considered, the costs of the polymer SC and the conventional concrete systems are often competitive.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH01-020

AUTHOR(S): Sperry, P. E.

PAPER TITLE: Summary of the Conference

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 441-447

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Economical applications of SC include: (1) staged support of large underground excavations, (2) encasing short reaches of steel sets in otherwise unlined tunnels, (3) supporting odd-shaped excavations, (4) sealing rock surfaces, (5) channeling water flows, (6) temporarily supporting ground with a short stand-up time, and (7) rehabilitation of deteriorated tunnel linings. The method of support must be compatible with the method of boring. SC must be applied to the full design thickness

ASAP. SC for support must be in a closed circle or tied to an unyielding buttress. A 28-day CS of 3 to 4 ksi is reasonable. Use of 1/2 inch aggregate is recommended for high strength SC, with 3/4 inch aggregate discouraged. For quality SC, compatibility of ingredients is essential and should be investigated in advance. The lack of experienced nozzle operators restrains the use of SC. QC is an essential and requires much more cooperation than for other types of construction. Research suggestions include: (1) develop improved design criteria and specifications, (2) investigate types of reinforcement, such as welded wire vs chain-link fabric, and optimum opening size, (3) determine long-term effects of accelerators, (4) determine factors which affect accelerator/cement compatibility, (5) determine why CS decreases with increased accelerator, (6) continue regulated set cement and fiber reinforced SC research, (7) develop improved SC handling systems which require less space for tunnel headings, (8) develop better accelerator feeders, (9) determine optimum nozzle configurations and water pressures for various configurations, (10) establish standard tests for rebound quantity, early strength, W/C ratio, and bond strength, and (11) determine the threshold level for airborne accelerator causticity and its long term effects.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH02-001

AUTHOR(S): -0-

PAPER TITLE: Specification for Materials, Proportioning, and
Application of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication 506.2-77
(Revised 1983)

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: March, 1989

PAGES (papers): -0-

TOTAL PAGES (books): 7

DISCUSSION: -0-

KEYWORDS: concrete construction, concretes, mix proportioning,
placing, quality control, shotcrete, specifications

REVIEW: Provides the latest design standard for SC which may be
cited in project specifications.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH02-002

AUTHOR(S): -0-

PAPER TITLE: Recommended Practice for Shotcreting

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Standard 506-66

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: March, 1966

PAGES (papers): -0-

TOTAL PAGES (books): 25

DISCUSSION: -0-

KEYWORDS: ACI standard, admixture, curing, delivery hose, dry mix
shotcrete, gun, nozzle, nozzleman, pneumatic feed,
positive displacement, rebound, wet mix shotcrete

REVIEW: Recommendations are given on the applicability of SC to
different types of construction, material requirements,
and application procedures, covering both the wet-mix and
dry-mix processes. QC/QA testing is discussed. The need
for experienced crew is emphasized.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-001

AUTHOR(S): Scanlon, J. M.

PAPER TITLE: Recent Research on Shotcrete by the US Army Corps of Engineers

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 17-28

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: USACE has used SC to repair "honeycomb" areas in new construction as well as structural rehabilitation. USACE looked at both wet and dry processes. Bonding efficiency higher for SC to old SC (almost 100%) than for SC to old concrete. Permeability was low for all mixes, but almost 4 times higher for dry process. Accelerators decreased the 7-day strength. Direct tensile tests recommended for bond strength and uniformity. Most properties similar to standard (dense) concrete. For rehabilitation, steel

fibers have been successful, since low permeability limits corrosion.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-002

AUTHOR(S): Seabrook, P. T.

PAPER TITLE: Properties of Shotcrete on Construction Projects

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 29-44

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Relationships were plotted for compressive strength (CS) vs. Time, Modulus of Rupture (MR) vs. Time, Ratio of MR to CS vs. Time, log of MR vs. CS ($MR=0.74*CS^{0.82}$), CS vs. Absorption and Voids, and MR vs. Absorption and Voids. SC found to be very similar to a high quality conventional concrete (about 5000 psi CS and 0.45 W/C ratio). A unique property of SC is high early flexural strength.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-003

AUTHOR(S): Schutz, R. J.

PAPER TITLE: Properties of Shotcrete Admixtures

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 45-58

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Accelerators are topic here. They work only in dry process SC. In wet process, the cement has already reacted with the water, and the hydration cannot be accelerated significantly. In addition, premature stiffening can be induced even though early strength is not accelerated. Inorganic accelerators induce quick-setting, but reduce ultimate strengths by their interference with W/C reaction. Organic accelerators induce early set and early strength gain with no penalty to ultimate strength. Rebound is a function of W/C

ratio. There is a tendency to shoot accelerated SC at less than optimum W/C ratio, which causes higher rebound. Accelerators are cement sensitive and should be pretested with the cement to be used.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-004

AUTHOR(S): Bauder, W.

PAPER TITLE: An European Accelerator Manufacturer's Views

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 59-65

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Three main types of accelerators: (1) carbonate and/or aluminate powders, (2) aluminate liquids, and (3) silicate (waterglass) liquids. Noted is difference between early and final strength, which should be considered on a case by case basis. Loss in final CS may be 10-40%, depending on dosage (2-12% of cement weight). For (2) above, almost flash set is achieved with a moderate loss of final strength. For (3) above, slower initial set, but little effect on final strength. Also, cohesion is increased, allowing thick layering in single

passes. Liquid accelerators are recommended over powders, because controlled dosage is available and rapid setting is possible without danger of clogging.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-005

AUTHOR(S): Kaden, R. A.

PAPER TITLE: Fiber-Reinforced Shotcrete Ririe Dam and Little
Goose (CPRR) Relocation

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
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York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 66-88

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Fibrous SC was used instead of conventional SC with wire fabric, with much lower bid cost (about 40% lower), even though the fiber costs exceed the wire fabric costs, since the fibrous SC allowed a reduction in total quantities (thickness). Other conclusions were that fiber-reinforced SC: (1) had improved tensile strength and strain to failure, (2) showed less cracking, and (3) provided microreinforcement across discontinuities.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-006

AUTHOR(S): Packham, G. R.

PAPER TITLE: Admixtures in Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 89-96

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This paper is basically an advertisement for WALLCRETE
(also called ACCRETE), which is a product of Wallco
Chemicals Limited. They use a powder dispenser and note
the danger of lack of mixing between cement and powder.
They suggest a WALLCO ADMIXTURE DISPENSER for good mixes.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-007

AUTHOR(S): Rutenbeck, T.

PAPER TITLE: Shotcrete Strength Testing - Comparing Results of
Various Specimens

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 97-105

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This paper notes the lack of standardization of SC testing. For thin linings, cores with L/D ratios of < 1 were utilized. For SC specifications, the specimen size should be specified with the strength requirement because different sizes give different strengths. Bureau of Reclamation is developing strength relationships for SC.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-008

AUTHOR(S): Peters, J. C.

PAPER TITLE: Wastewater Treatment During Tunnel Construction on
Bureau of Reclamation Projects

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 106-114

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Addresses only general environmental concerns, nothing
specific to SC.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-009

AUTHOR(S): Valencia, F. E.

PAPER TITLE: Evaluation of Shotcrete Application Under Field
Conditions

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 115-148 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Design principle often used for SC is "when in doubt,
build it stout." Paper points out that only successes
with SC are reported, and that other results not reported
include non-productive shifts, poor quality SC, excessive
rebound, excessive dust, equipment failure, and a "never
again" attitude of field personnel. Total program
reviews are recommended for SC projects. Complete design
of a program is discussed, including material selection,
equipment calibration, and personnel training. A two-day

course outline was presented, with separate courses for supervisors and SC crew members. Supervisors were given more emphasis on principles, including mix design and QC/QA evaluation. SC crew members were given more emphasis on practical applications, such as use of equipment and placement techniques. Conclusions were that specified CS could be achieved even with crews having limited experience with SC. Apprehension of SC crew members was dispelled when properly instructed, and increased efficiency justifies cost of training. NOTE: This paper is an excellent summary of a "total program" for instituting SC utilization.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-010

AUTHOR(S): Parker, H. W., Fernandez-Delgado, G., and Lorig, L. J.

PAPER TITLE: A Practical New Approach to Shotcrete Rebound Losses

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 149-187

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Dynamics of rebound is idealized into 2 phases. Phase 1 is the time during which a thin cushion-like layer of SC is established, with high rebound rate (from 50-100% of material weight falling in any given time period). Phase 2 is the period when incoming SC impacts a relatively soft cushion of fresh SC, with increasing reduction in rebound. Transition from Phase 2 back to Phase 1 can occur when accelerators are used, when dry mixes are used, when there is a time-lag before returning the nozzle to a particular spot, or when multiple-lift SC

techniques are used. Moving the nozzle incrementally, near the edge of the build-up, often masks the transition between Phase 1 and Phase 2. Material delivery rate (MDR), rebound rate (RR), and yield rate (YR) are important parameters needed to study rebound, where $YR = MDR - RR$. Therefore YR is a indicator of which is primary phase, with high YR during Phase 2 and low YR during Phase 1. Rebound rate ratio (RRR) is the ratio of RR to MDR. RR or RRR vs. Time are similar, but it is more appropriate to plot RR or YR vs. Wall Thickness. Average rebound (percentage rebound) is used by industry and can lead to confusing results, since Average Rebound (RAVE) is decreasing when the true RR is constant (Phase 2). Thickness should be considered in these tests. Multiple tarp testing to determine true RRs confirmed that the true RRs were nearly constant before (Phase 1) and after (Phase 2) the critical thickness was reached. RAVE was highly dependent on wall thickness and duration of test. Increased accelerator dosage up to optimum appeared to reduce RAVE, but dosage above optimum increased RAVE. Phase 2 RR was significantly reduced by the use of steel fibers, although there was little change in RAVE. The reduced RR with steel fiber mixes was attributed to improved mix and shooting conditions rather than the mere presence of the fibers. Differences in water content and consistency were noted. W/C ratio controls strength gain, but consistency has biggest effect on RR. A wetter consistency reduces RR, up to the wettest stable consistency, where sloughing increases RR. Low ambient temperature causes a minor increase in RR. Increased mix water temperature can increase cohesion and reduce RR up to an optimum mix water temperature, above which over-accelerated stiffening increases RR. A homemade "long (14 ft) nozzle" improved mixing and decreased RR as compared to a conventional short (18 in) nozzle and also gave higher strengths. Hardness of the wall had little effect of RR during Phase 2. Hardness of the wall increased the rebound distance during Phase 1, but had little effect on RAVE. A standard rebound test is proposed which uses 2 guide boards to allow successive shooting to thicknesses of 4.0 in. and 0.5 in. separately with separate tarps. This test will allow evaluation of Phase 1 and Phase 2 RR, as well as RAVE. For field evaluation, test surfaces should be similar to actual surfaces to estimate rebound losses, defined by the

overshoot factor ($OSF=1/(1-RAVE)$), and actual total SC thickness should be used to measure RAVE.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-011

AUTHOR(S): Kobler, H. G.

PAPER TITLE: Review of Dry-Mix Coarse-Aggregate Shotcrete as
Underground Support

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 188-200

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author was directly involved in the first shotcrete use in Canada and gives a historical perspective as well as a general review of dry-mix shotcrete use. SC has gotten a bad reputation in some circles primarily because of "fast buck" promoters and "instant shotcrete" experts. In some cases, impossible benefits were promised and often the "expert" was most interested in selling an expensive additive. The basic principles of dry-mix shotcrete have changed very little in over a decade.

Although a discharge nozzle is normally used, improved results have been achieved in some cases by removing the nozzle and simply cutting back the discharge hose when it becomes frayed. The required water is usually dispensed at the nozzle, but improved quality and reduced rebound is achieved when a single or double watering O-ring is positioned at 3-6 meters back from the discharge end. The added water is controlled by the nozzle operator and the quality of the SC is dependent on the skill of the nozzle operator. Unsuitable aggregate will produce inferior SC, regardless of the amount of cement added. Early strength is often a controlling factor in ground support situations. Compatibility of chemical accelerators with the cement to be used should be checked in advance. For ground support, only the initial application needs to be accelerated. Mixes are available which set in 15 seconds and are completely hard in 1 minute. Liquid accelerators are usually better because mixing, dispensing, and control are simplified. Inexpensive accelerators based on calcium chloride or sodium silicate often outperform expensive accelerators. Rebound is highly dependent on the skill of the nozzle operator. SC is most cost-effective for ground support when used in difficult geological conditions. SC will not perform well in very wet or water-bearing ground. Excessive dust from the dry-mix process may be a problem. Health effects of chemical accelerators have not been established. Minimum thicknesses should be a major concern for QC of shotcreting in ground support applications, since thin layers of shotcrete may have a "sound" appearance which could lead to a false sense of security. "It (shotcrete) always performed satisfactorily wherever and whenever applied with proper technological criteria, and based upon sound judgment ... and field tested expertise."

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-012

AUTHOR(S): Morgan, D. R.

PAPER TITLE: Steel Fiber Shotcrete for Rehabilitation of Concrete Structures

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Transportation Research Record 1003

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: -0-

CORPORATE AUTHOR OR PUBLISHER: Transportation Research Board,
National Research Council,
Washington, DC

MONITORING AGENCY: -0-

PUBLICATION DATE: 1984

PAGES (papers): pp. 36-42

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Steel fiber reinforced shotcrete (SFERS) has been used in many cases for repair. SFERS is particularly attractive for cases where mesh-reinforced SC is proposed. Marine uses have been common, with corrosion being a problem only at the surface and in cracks, with superior performance reported when compared to conventionally reinforced structures. There has been little use to date of SFERS for repair of conventional structures, although it has been used to repair impact damage in marine structures. Summaries of physical properties of SFERS indicate that it is generally superior to conventional repair techniques. CS is similar to standard mixes, but

post-peak stress-strain behavior is flatter, making it attractive for resistance of dynamic loads. Fibers tend to be oriented parallel to the surface, and tend to increase the flexural strength in the plane of the layer. Toughness is the major justification for steel fiber utilization, with a toughness index of 4 to 10 times higher than the control. Impact resistance tests indicate significant improvement with steel fibers, with as much as 10 times the number of blows to failure as the control (varies with percent of fibers). Fatigue tests on beams indicate improved fatigue life with steel fiber reinforcement of standard concrete, which implies improved fatigue life for SFRS. Published data indicate that bond strengths greater than 500 psi are possible with SFRS. In general, bond strength has been shown to be significantly greater for SC than for conventional concrete. Durability is not a problem as long as the matrix retains its inherent alkalinity and remains uncracked. Studies in severe environments have shown that carbon steel fibers will not oxidize significantly as long as crack widths are less than 0.003 in. In addition, much of the composite strength may be retained for cracks up to 0.012 in., because the fibers can tolerate significant reduction in diameter with minimal effects.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-013

AUTHOR(S): Chynoweth, G. L.

PAPER TITLE: Properties of Latex-Modified Shotcrete Beneficial to
Concrete Repairs

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Transportation Research Record 1003

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: -0-

CORPORATE AUTHOR OR PUBLISHER: Transportation Research Board,
National Research Council,
Washington, DC

MONITORING AGENCY: -0-

PUBLICATION DATE: 1984

PAGES (papers): pp. 42-46

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Latex-modified shotcrete (LMS) is presented as an improved material for SC repairs. The primary benefits of using LMS is its enhanced durability and improved bond. The latex bonds with the cement paste and its flexibility and tensile strength limit the formation of microcracks during curing and reduce the permeability. CS is reduced for a LMS compared to standard SC. However, design strengths are still easy to achieve. Flexural, tensile, and bond strength are improved. Bonding is improved for dynamic loads because the LMS can undergo strains as well as transmit tensile stresses. Shear bond strength is usually governed by the strength

of the concrete. Permeability is low and absorption is low, leading to excellent freeze-thaw resistance. The bond strength of polymer to cement and the elasticity of the polymer results in a modulus of elasticity of about 50% of a conventional SC. Tests indicate the combination of high tensile strength and low modulus of elasticity makes LMS very impact resistant. Impact tests indicate that about 5 times more blows were required to develop the first crack compared to conventional SC. Traditional mix designs may need modification for LMS, since LMS mixes are designed for maximum durability instead of maximum strength. LMS designs are usually rich with a relatively low W/C ratio. Flexural strength and absorption tests should be used for QC instead of strength tests, since addition of latex does not improve the CS. Other admixtures should not be used unless specified by the manufacturer. A long nozzle is recommended to provide adequate mixing. Quality of LMS depends on the skill of the nozzle operator. The surface of LMS will develop a surface film which must be removed before added more layers. Brooming will break the film unless the final set is established, requiring sandblasting or waterblasting. Minimum film formation temperature (MFT) is normally around 45 degrees F.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-014

AUTHOR(S): Cedarqvist, H.

PAPER TITLE: Fiber Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Journal of Ferrocement (Bangkok)

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 18, Number 3

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: July 1988

PAGES (papers): pp. 301-307

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: metal fibers, nozzles, prefabrication, shotcrete

REVIEW: The reference describes a fiber shotcrete method to prefabricate thin-walled products or to repair/strengthen existing structures. The method uses a continuous feed from spooled steel wire which is cut within a spray gun and ejected by compressed air within a shotcrete mix. This method is presently used in Sweden, Finland, and Australia primarily because of the good fiber orientation which can be achieved.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-015

AUTHOR(S): Suprenant, B.

PAPER TITLE: Making Good Concrete Better

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 33, Number 8

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: August, 1988

PAGES (papers): pp. 743-748

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper addresses concrete curing in general, but also makes recommendation for SC curing. For SC, the best method is to keep the SC continuously wet for 7 days while maintaining a temperature > 40 F. Wheel-mounted fog sprayers with automatic timers may be economical for large jobs and hand sprayers are ideal for small jobs. Other options include wet burlap or sprayed curing compound. The curing compound should be used when drying conditions are not severe, since water can evaporate through the curing membrane. For rough textured surfaces, the compound should be applied thicker than usual, with a coverage rate of about 100 square feet per gallon. Don't use curing compound if the SC surface will be painted or will receive another layer of shotcrete.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-016

AUTHOR(S): -0-

PAPER TITLE: State-of-the-Art Report on Fiber Reinforced
Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication 506.1R-84

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1984

PAGES (papers): -0-

TOTAL PAGES (books): 13

DISCUSSION: -0-

KEYWORDS: fiber reinforced concretes, reviews, shotcrete

REVIEW: Comprehensive summary on fiber reinforced SC, including steel, glass, and polypropylene fibers. The inclusion of fibers generally improves material properties including ductility, toughness, flexural strength, impact resistance, fatigue resistance, and compressive strength. Of the 3 fiber types, steel fibers are most commonly used. The summary describes fiber types, typical material properties, batching and mixing, installation, and applications.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-017

AUTHOR(S): Barnard, P. D. and Tobin, R. E.

PAPER TITLE: Structural Quality Lightweight Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 123-138

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC can vary in unit weight from 40 to 200 pcf. Lightweight structural SC is in the range of about 90 to 120 pcf with CS of at least 2500 psi. In the US, most lightweight structural SC is made with manufactured expanded aggregates from clays or shales by the rotary kiln method. Only the dry-mix process was discussed in this paper. Cost is a major factor in the use of lightweight structural SC because of reduced dead loads which allow reduction of columns and footings and increase seismic resistance. Use of composite beams of steel and lightweight SC can save cost yet improve structural performance. The thermal conductivity of lightweight SC is about 1/3 of normal SC, so that it

provides much better insulation when used in thin surface applications. Similarly, lightweight SC has been used to improve the fire resistance capacity of structures for periods greater than 1 hour. One of the great merits of SC is the savings on form costs. Mechanization of SC equipment can reduce the number of laborers required to place the concrete. SC can be delivered into congested spaces. In many cases, SC can be placed more rapidly than conventional concrete. CS of 2500 to 6000 psi can be achieved with most lightweight aggregate SC mixes. Properties of the lightweight aggregate can usually be supplied by the producer (often more accurately than from sample tests). Mix proportions vary from 1:3 to 1:5 by bulk volume. Some operators have incorporated weighing equipment into their batching facilities to minimize bulking of aggregate particles due to surface moisture. ASTM allows up to 10% variation in unit weight, but most producers maintain a lower percentage of weight variation on their lightweight fines. Typical strengths and gradation are tabulated. It has become more common to make CS the primary acceptance criterion. Typical methods for producing CS samples include test panels and shooting into a 6x12 inch cylinder mold made by shaping 1/2 inch galvanized hardware cloth around a standard mold. Use of lightweight aggregate in SC can usually be done only by the dry-mix process, due to possible absorption of water by the aggregate in the wet-mix process. Placement is similar to a sand-cement mix, although less air pressure is needed (typical 45 psi air pressure in gun, with an additional 15 psi of water pressure. Rebound loss varies from about 15 to 33% by volume. Finishing is similar to standard SC. Curing may be done by continuous water spray or by curing compound, with the curing compound method becoming increasingly popular.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-018

AUTHOR(S): Zynda, S. G.

PAPER TITLE: Properties of Sand-Mix Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 155-164

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC has often been oversold, with reports of W/C ratios of 3 gal/sack (0.27 by weight) and ideal cylinder compressive strengths of 10 ksi. Knowledge of true mix proportions is critical. Few papers report the mix at the gun. A 1:4.5 mix by volume is typically a 1:4 mix by weight. Proportions in place may be determined by washing the mix over a #200 sieve (assuming only cement passes) or by testing the CaO content, which can be done on hardened samples (assumes no CaO in sand). In general, a 1:4 mix at the gun produces a 1:3.25 mix in place with a rebound mix of about 1:10. A standard test has not been developed for nozzle velocity, but a typical reported value of 450 fps is disputed. The optimum

velocity will have a relatively small rebound and make a slight sheen appear on the SC surface, indicating maximum density of SC. Wire basket cylinders have produced misleading results, typically almost double the strength of comparable core samples. The author feels that SC designs should be based on strengths no more than 4000 psi. Typical SC unit weights for overall mixes, 1:4 mixes, and dry weight are 144, 142, and 134 pcf, respectively. The moisture content is similar to any other concrete at the same slump (typically zero for SC). Addition of water causes bulking unless sufficient water is added to make the mix plastic. The maximum density occurs at the point of impending sag, or the wettest possible stable consistency. Usually decreased W/C will increase SC CS, unless the water drops below the optimum total water content, which will decrease strength.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-019

AUTHOR(S): Litvin, A. and Shideler, J. J.

PAPER TITLE: Laboratory Study of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 165-184

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Summarizes a laboratory study of SC properties, with test slabs shot and cut. Testing included CS, E, FS, drying shrinkage, creep, absorption, durability, and water permeability. Curvilinear fitted relationships are shown for W/C vs CS, CS vs E, drying shrinkage vs net water content, creep strain vs age, and percentage change in fineness modulus vs net W/C by weight. Tabular results of freeze-thaw durability and absorption tests are also presented.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-020

AUTHOR(S): Coho, R. W., Jr.

PAPER TITLE: Volumetric Proportioning, Blending, and Mixing

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 101-103

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper describes advances in the state-of-the-art of SC mixing equipment which have allowed an improvement in the uniformity of SC mixes. Use of batch mixing has created problems with uniformity. The newer method uses ribbon feeds to provide a uniform proportional feeding. Some separation still occurs in dry mixed materials with subsequent handling into the dry SC machine. This problem is relatively minor with the wet-mix process. However, this method of producing wet-mix process SC

requires a uniform injection of water into the mixture in proportion to the ribbon feed of aggregate. Use of volumetric proportioning (weight equivalents) has resulted in improved continuous uniformity.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-021

AUTHOR(S): Steenson, H. N.

PAPER TITLE: Using Accelerator - Wet Process

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 104-113

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Both dry-mix and wet-mix processes are discussed. The quality of dry-mix SC depends on: (1) a well graded aggregate curve, (2) the mix prior to adding nozzle water must have at least 2% moisture (for dust suppression), but less than 5% moisture (to avoid clogging hoses), (3) the nozzle operator determines the W/C ratio, and (4) rebound is determined by the factors previously mentioned, as well as the angle of shooting, the distance of the nozzle from the surface, the air and water pressure

(should be 80 and 70 psi, respectively), and control of the feeder system (including the feed of accelerator). Dry-mix process can provide 4-5 cubic yards per hour when handled manually, with up to 8 cubic yards per hour when mechanized. Rebound varies between 25% and 30%. Wet-mix process has typically been unable to use accelerators, which has led to a domination of the SC market by the dry-mix process. Positive displacement equipment is available to pump the wet-mix SC, but addition of accelerators has been a problem. The typical powdered accelerators must be applied at the nozzle, but is almost impossible to meter or apply uniformly. A new system has been developed which utilizes a log of accelerator created by hydraulically compressing the powder. The log is fed hydraulically into a wire brush, which grinds and feeds the powder at a uniform rate. A prototype model of the wet-mix accelerator log feeder was tested in an underground mine in Arizona with a comparison to dry-mix process. The wet-mix process had a reduction of material of 25%, due to decreased rebound. There was a 129% improvement in underground man hours per cubic yard for the wet-mix process. The wet-mix process produced 28-day CS of greater than 4000 psi and was comparable with the dry-mix process SC. Other advantages of wet-mix versus dry-mix included: (1) the dust problem was abated, (2) the powder logs reduced the powder handling problem and the powder contamination problem, (3) the equipment cleaning was easier, (4) maintenance costs are reduced, (5) the quality of the SC was no longer controlled by the nozzle operator (W/C ratio), and (6) production rate was 10 to 12 cubic yards per hour.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-022

AUTHOR(S): Case, L. A.

PAPER TITLE: Quality Control and Application - New Melones
Project

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 235-245 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This project successfully used SC, in conjunction with 10
and 15 foot rock bolts, as the primary tunnel support
method. Only one incident of potential ground failure
occurred, when a 30 foot long crack appeared in one
section after a 2 inch initial application of SC.
Subsequent application of 4 inches of SC stopped further
movement. Specifications required a dry-mix process SC
with a minimum 6.3 sack cement content and maximum

aggregate size of 3/4 inches. Mix design was the responsibility of the contractor, but CS of 670 and 500 psi were required for ages of 8 hours and 28 days, respectively. CS specimens were NX size cores removed from in place SC. Pre-job investigation resulted in an accumulation of confusing and contradictory information. QC was the responsibility of the contractor, with a separate group whose head reported directly to the project management. Breakdowns of accelerator dispensers were frequent, with work continuing with hand measured quantities of accelerator added. SC testing was done on samples from the SC walls and also from test panels. The panel tests were used to evaluate early strengths, and had samples sawn to form 3 inch cubes. Other samples were 3 inch cores from the SC walls, which were thickened to 8 to 10 inches in the sampling areas. CS was the only testing, with no tests for bonding. The CS from the 3 inch cubes were reduced using a factor of 0.86 to correlate with the 3 inch diameter core. Instrumentation to measure stresses in the rock mass were installed, but results were inconclusive.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-023

AUTHOR(S): Rutenbeck, T.

PAPER TITLE: New Developments in In-Place Testing of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 246-262

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The 6x12 inch cylinder is useful for conventional concrete because it is representative of the strength of the in-place concrete. While it possible to shoot a 6x12 cylinder with SC by shooting into a wire mesh form, this is not representative of the in-place SC. A convenient and common method of QC for SC is test panels. Cores from the finished lining gives the most representative results, but they may have damage due to the less than ideal conditions in the field. In addition, the cores

cannot be taken at an early age. CS of 750 and 1000 psi are needed for 4 inch and 2 inch cores, respectively. Commercially available testing devices include the Windsor probe and the rebound hammer. The Windsor probe is a penetration test which is very useful for relative strength comparisons, but the direct correlations with CS must be made on a mix-by-mix basis. The rebound hammer measures the rebound of a rod forced against the surface by a spring load. This device is also useful for relative strength comparisons. There is another test, which is recommended by the author, the pullout test. A bolt with a washer brazed to the head is embedded in the fresh SC. A truncated cone of SC is extracted by pulling the bolt from the material through a steel ring. The result is a pullout failure stress which can be related to the CS. Parameters which are used to compute the pullout failure stress are the force of pullout, the surface area of the cone, and the cone angle. Tests with apex angles within the range of 60 to 68 degrees are comparable. Pullout tests on panel for 5 SC mixes gave a correlation coefficient of 0.876 for pullout failure stress versus CS of 2x4 inch cores (based on fitted equation $Y=3.96X-40$). When 4 inch cubes were tested, the fit was parallel, but the CS of the cubes was slightly higher ($Y=4.01X+370$, $CC=0.878$). A statistical analysis indicated that the correlations were highly significant.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-024

AUTHOR(S): Reading, T. J.

PAPER TITLE: Corps of Engineers Studies of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 263-276

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author notes that SC is a general term, and designers should specify whether they mean mortar of coarse aggregate SC, with or without accelerator, etc. The USACE has increased its use of SC "because of the surprisingly good performance of many old SC applications." These include lock wall repairs in the severe climate of northern Michigan in the 30's, World War I concrete barges, and others, often completed with little or no QC. There have also been numerous examples

of failures, mostly due to poor field practices. A major cause of failure of SC is inadequate preparation of old surfaces. A thin veneer of SC cannot permanently repair deteriorated concrete, but may be an economical approach with occasional renewal. Normal SC placed by qualified personnel should have CS greater than 500 psi, and can go as high as 10000 psi. One of the strong points of SC is its excellent bond with old concrete, sound rock, and other materials. The drying shrinkage is typically higher than for conventional concrete, but is usually not a problem. SC has been durable, and roughly equivalent to conventional air-entrained concrete rated satisfactory for use in freeze-thaw conditions. The USACE has moved cautiously into the use of SC for ground support, due to lack of design procedures and doubts about QC. The USACE is now preparing a design manual for tunneling which reflects a wider use of SC. Use of SC for ground support usually necessitates the use of an accelerator. Testing on various mixes with accelerators indicated a wide variation in the properties and rate of acceleration. In addition, the causticity of the mixes was noted. More research on accelerated mixes is needed. The New Melones tunnel job in California is presented as a case study for successful use of SC by the USACE. Despite several problems and questions (such as the rate of adding accelerator), the SC has performed well, with instrumentation showing practically no movement of rock. Cores from the SC lining were much more variable than for conventional concrete. In addition, lab strengths could not typically be duplicated in the field. The author recommends pre-qualifying the mix, equipment, and procedures by using test panels. After the job, cores from the structure are the preferred method of QC, but use of test panels may still give good results. "Rebound is the greatest enemy of sound SC." Trapping of rebound give the SC a laminar structure. The appearance of the surface is no indicator of the overall quality of SC. There are two general QC tests of interest: (1) determining the proportions of the mix in place and (2) strength testing. One simple control test is a water content of fresh SC. The more laborious washout test can be used to determine the cement content with fair accuracy. There are tests available for determining the cement, water, and void content of hardened SC, but they are difficult and expensive, and therefore used primarily

for research purposes. The USACE generally specifies a minimum strength of 700 psi at 7 hours. The SC is too green for coring, so cubes from test panels are typically used to evaluate the early strength. The USACE expects 2000 psi at 24 hours, and can take cores at that time. Other tests which have been tried include pullout tests, Schmidt hammer, and Windsor probe. Pullout tests were disappointing. The Schmidt hammer tests were fair, with the rough surface of SC creating problems. The Windsor probe shows considerable promise, but is not sufficient for strengths less than 1500 psi. The USACE has also used regulated set cement as an alternative to accelerator admixtures. Temperature sensitivity was a problem for the reg-set cement. The USACE has done some work with fiber reinforced SC, with a case study described of a section at the Ririe Dam in Idaho, using a mix of 240 pounds of steel fibers per cubic yard. The fibers were 16 mil in diameter and 3/4 inches long. The mix gave 28-day flexural strengths of 900 psi (less than the full potential), but had increased ductility.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-025

AUTHOR(S): Anderson, G. L. and Poad, M. E.

PAPER TITLE: Early Age Strength Properties of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 277-296

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Bench tests were used to determine which fast set agents and cements were to be used in the program. Based on ASTM C266 for time of setting, the fastest setting mixes were chosen for CS testing with 2-inch cubes (ASTM C109). All cubes used a mortar standardized to a sand-cement ratio of 2.75. Accelerated mix mortar cubes used a W/C ratio of 0.43. Results are presented in tables and graphs. Based on the results, the following were selected for further evaluation: (1) Type III cement with

Tricosal, (2) Type III cement with Isocrete powder, and (3) regulated set Portland cement (RSPC), with and without soda ash. Test panels were made using both dry-mix and wet-mix processes. Results of CS testing are included in graphs and tables. Conclusions were that high-early SC is possible by both dry-mix and wet-mix processes and that the RSPC produced higher early strengths than the SC made with a fast setting admixture. No more than 3% accelerating admixture should be used, because ultimate strength is inversely proportional to the percentage of accelerator.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-026

AUTHOR(S): Jones, R. A. and Mahar, J. W.

PAPER TITLE: Instrumentation to Monitor Behavior of Shotcrete
Support Systems

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 297-319 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Case study data is included for two test sections in the Washington, DC subway tunnels. The major instrumentation type were double position, rod-type extensimeters. Both bonded resistance gages and vibrating wire gages were embedded to measure strain. Extensimeter readings less than 0.05 inches and strain readings of less than 150 microstrain correspond to a stress increment of about 400 to 500 psi and indicate satisfactory behavior. In the

SC-rock bolt section of tunnel, rock block movements were typically between 0.02 and 0.03 inches. Displacements in the steel rib-SC section were typically greater than 0.1 inches. This is indicative of the early support provided by the rock bolt-SC system. Cracks occurred in the SC when displacement was greater than 0.05 inches or strain greater than 150 to 300 microstrain occurred. Most of the cracks occurred near protrusions where the SC thickness was about 1 inch. Based on the case study data presented, the author recommends the use of instrumentation on tunnel projects to monitor rock movements.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-027

AUTHOR(S): Blanck, J. A.

PAPER TITLE: Shotcrete Durability and Strength - A Practical
Viewpoint

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 320-329 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Many factors influence the strength and durability of SC,
including mix design, batching, mixing, and application.
The selection of cement and accelerating admixture should
be based on a realistic laboratory compatibility test.
The following Gilmore setting times should be attainable
with the cement and admixture for a particular job:
(1) initial setting in 3 minutes maximum and (2) final
setting in 12 minutes maximum. Proposed compatibility

tests include initial and final Gilmore setting times (ASTM C266) for additive concentrations of 1, 2, 3, 4, 6, and 8% of the cement content by weight. The gradation of the mix affects pumpability but has little effect on CS. However, the flexural strength, shear strength, and bond strength appear to increase in mixes containing aggregate of at least 1/2 inch. Mixes with crushed rock usually show higher strengths than mixes with gravel. However, crushed rock is more difficult to apply and causes more wear to equipment, so gravel mixes are usually recommended. The cement content is usually 7 bags per cubic yard for underground applications. A 6 to 6.5 bag mix is usually adequate for a 5000 psi SC mix, because the in-place mix is richer due to rebound. Use of admixtures to increase early strength usually decreases the ultimate strength. With careful testing, a high early strength (500 and 1000 psi at 3 and 5 hours, respectively) can be achieved using a 2-3% admixture, with a loss in ultimate strength of about 25% at 28 days and about 15% at 90 days. Based on lab studies, regulated set cements are superior to mixes with accelerating admixtures in both early strengths and also ultimate strengths, but field performance is still not proven. No single test exists which will give early strength results on field mixes. Pullout tests seem to give fair readings in early testing and the Windsor probe gives good readings for SC with CS > 1500 psi. The author has also used wire-basket cylinders and cubes from panels to evaluate strengths less than 1000 psi. In situ testing of SC which is at least 24 hours old is typically done with standard coring procedures. Flexural strength may be a better way to evaluate in-place SC, since it is more sensitive to lamination. Panel tests are usually the only way to do flexural strength tests. Most SC failures can be traced to poor workmanship, improper mix design, poor equipment, inexperienced operators, of a lack of understanding of the process.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-028

AUTHOR(S): Parker, H. W.

PAPER TITLE: Current Field Research Program on Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 330-350 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A field study was made to evaluate the properties of
regulated set SC and steel fiber SC. Reg-set cement SC
can achieve a CS of 1000 psi in 1 hour. Reg-set cement
uses calcium fluoroaluminate, and sets within 10 minutes
at room temperature. The advantages of reg-set SC are:
(1) no accelerator required, (2) early strength of
reg-set SC is much higher than for conventional SC, and
(3) no reduction in 28-day CS. The disadvantages of
reg-set SC are: (1) hot water may be required, (2)

special handling is needed to permit immediate use after mixing, and (3) the cement is more costly. Use of steel fibers provide extra tensile and flexural strength in SC. Usual fibers for SC are about 1 inch long, with diameter about 1/4 of paper clip wire. The fibers fail in bond, so that longer fibers are more effective. However, long fibers do not mix well, so that the 1 inch length is a compromise between strength and workability. The fibers are furnished in boxes of 40 to 50 pounds each, and can be sprinkled into the mix at a rate of 1 or 2% by volume (3 to 6% by weight), or about 132 to 264 pounds per cubic yard. Balling of fibers can be a problem. A field study on the experimental mixes showed that coarse-aggregate mixes of reg-set SC and steel fiber SC can be applied successfully with the dry-mix process. Rebound tests indicated a high rate of rebound for the first 1/2 inches of rebound (more than 5 times the rate for subsequent application). The rebound contained a high percentage of coarse particles. A high percentage of steel fibers rebounded, but the fibers were not missile hazards. A homemade long nozzle with a single water ring about 14 feet behind the hose tip provided more uniform mixing. Stop-action photography indicated that particles were moving toward the wall at a rate of 100 to 200 feet per second. The reg-set SC was 3 to 10 times stronger than conventional SC after a few hours. After 28 days, the CS of reg-set and conventional SC were generally greater than 5000 psi. CS of steel fiber SC was less, but the ratio of flexural strength to CS was much higher. In addition, the steel fiber SC exhibited high post-crack resistance, with considerable load carrying capability even after a beam crack of greater than 1/4 inch.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-029

AUTHOR(S): Tilp, P. J.

PAPER TITLE: Summary of Workshop C

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 351-366 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Contains summaries of all the presentations for this workshop. A presentation was documented that was not included as a published paper. This was a presentation by Owen Richards on Pullout Test Research. Based on results of tests at the National Sand and Gravel Association (NSGA) laboratory, more widespread use of pullout tests were recommended.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-030

AUTHOR(S): Graham, J. R.

PAPER TITLE: Polymer Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 418-435 TOTAL PAGES (books): -0-

DISCUSSION: Discussion by Bates, R. C. on pp. 431-433, with
closure by author on pp. 434-435

KEYWORDS: -0-

REVIEW: Polymer-concrete (PC) consists of aggregate and monomer
mixed together using common procedures, and subsequently
polymerized at ambient temperatures following placement
of the material. The principal difference in polymer SC
and conventional SC is that a polymeric binder is used in
lieu of Portland cement and water. Dry-mix process was
used for application of polymer SC. Material
investigation was used to select a suitable monomer

system, suitable aggregate properties and grading, and a promoter-catalyst system, to optimize: (1) the cohesive qualities of the mix, (2) the properties of the cured material, and (3) the low temperature performance of the polymerization system. Screening tests indicated that a suitable monomer system contained 72% by weight MMA (methyl-methacrylate), 13% by weight TMPTMA (trimethylolpropane trimethacrylate), and 15% by weight Acryloid A-11 (primarily polymethyl methacrylate). Rapid cure of the monomer system was achieved by adding a polymerization catalyst-promoter system composed of benzoyl peroxide as catalyst and the promoter, n, n, dimethyl-p-toluidine in concentrations of 2% each by total monomer weight. Aggregate gradations were selected which would provide a cohesive mix with minimum rebound and a sound finished product. Two SC application techniques were used. The first used modified SC equipment to mix and deliver a final product. The second used a staged approach, with a heavy monomer spray followed by an application of dry aggregate to provide a laminating effect. In general, the polymer SC had CS exceeding conventional SC. Safety is a problem for the use of polymer SC, since the materials involved are volatile.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-031

AUTHOR(S): Manns, W., Nubert, B., and Zimbelmann, R.

PAPER TITLE: Shotcrete Tested

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Beton

DESCRIPTIVE BOOK NOTE OR EDITOR: Dusseldorf

VOLUME & NUMBER OR REPORT NUMBER: Volume 37, Number 8

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: August, 1987

PAGES (papers): pp. 317-319

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Accelerating agents, construction, deformation,
hardness, linings, loads, structural forms, shells,
shotcrete, tests, tunnels, stiffness, strength, mix
proportions

REVIEW: Review consisted of detailed abstract written in English,
with the actual reference written in German. Both
dry-mix process SC and wet-mix process SC with water
glass were examined to study the influence on strength
development and deformation of accelerating agents.
Accelerating agents are used to induce high early
strength stiffening and hardening. An important part of
modern tunneling techniques is the use of SC as the
lining at the heading, since the shell must be able to
bear relatively heavy loads after only a few hours.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-032

AUTHOR(S): Seabrook, P. T.

PAPER TITLE: Durability of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 11, Number 8

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: August, 1989

PAGES (papers): pp. 78

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Questions have been raised about the durability of SC. There is little published information on this subject, with most information coming from a small number of case histories. Concern has been raised about the lack of a rational method for determining the freeze-thaw durability of SC since it is not practical to entrain air in dry-mix SC and wet-mix SC often has less than optimum air void parameters. Some authors believe that traditional protection from freezing and thawing is not needed because of the special nature of SC. There is a general consensus that good-quality SC is durable, even in marine, chemical, and hydraulic exposures. SC has been a durable material for the restoration of concrete structures. However, there have been examples of SC

applications that have not yielded the level of durability sought by the owners, and guidelines to correct these problems are forthcoming.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-033

AUTHOR(S): Glassgold, I. L.

PAPER TITLE: Shotcrete Durability: An Evaluation

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 11, Number 8

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: August, 1989

PAGES (papers): pp. 78-85

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Air entrainment, durability, evaluation, freeze-thaw
durability, reviews, shotcrete

REVIEW: The author points out a common flaw in reported poor performance of SC, the extrapolation of short term results into long term "truths" that often contradict other successful applications and more conclusive data. He points out that so-called new observations are usually a reinterpretation of existing knowledge which do not enhance understanding of SC. There is a lack of technical data on the freeze-thaw durability of SC, probably due to timing. Interest in entrained air started prior to World War II, but the technology for entraining air was not developed until after the war. The first investigations of entrained/entrapped air in SC for durability was in the mid-1950s. Data presented by

Litvin and Shideler showed that SC could be durable and that the physical entrainment of specified amounts of air was not absolutely necessary to insure this durability. This confirms what many SC practitioners have observed over the years. "SC that is installed using the best of materials and practice can provide suitable and acceptable durability." Variability of reported data is noted as a cause of confusion about SC. The objectivity of many tests are in doubt, with extrapolated conclusions based on single-sampled data and derivations. While these field tests may be adequate for QC/QA, conclusions about long-term performance should be based on scientifically designed experiments. Much of the dissatisfaction with SC is neither detailed nor explained. The author states that the durability of SC is often controlled by the quality of the SC, with the SC quality influenced by: (1) design/quality control, (2) materials, (3) application equipment, (4) craftsmanship, and (5) placement technique. Application equipment is often overlooked in specifications, but may have a great effect on the SC durability. Many authorities believe that the quality of the in-place SC is directly proportional to the exit velocity from the nozzle (up to an optimum velocity). A series of high-speed photography tests with SC materials is suggested. The author points out that poor SC gun design can contribute to a nonuniform discharge, which in turn leads to low-quality SC. The use of a long nozzle, reduced chamber size, and increased frequency of chamber discharge can help alleviate these problems. It is also essential that the nozzle operator understand the impact of his workmanship on the quality of the produced work. Preliminary tests indicate that a nominal addition of silica fume to standard PCC has very beneficial effects on the durability of dry-mix SC, although it also increases the water demand of the mix. The overall conclusion is that certain non-air-entrained concretes can be durable, and that strength alone is not an absolute indicator of concrete durability.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-034

AUTHOR(S): Morgan, D. R.

PAPER TITLE: Freeze-Thaw Durability of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 11, Number 8

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: August, 1989

PAGES (papers): pp. 86-93

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Freeze-thaw durability, mix proportioning, performance
tests, reviews, shotcrete

REVIEW: SC has been used in North America for almost 80 years. Initially all SC was dry-mix process, but recent improvements in pumping equipment and materials technology (such as superplasticizers and silica fume) have resulted in increased use of wet-mix process SC. The paper details a review of SC durability based on case history data and also on the results of laboratory evaluations. Most case histories of performance are limited to visual assessment of the performance of various structures. Several laboratory studies and case histories are summarized. One of the results of the study was a summary on the mechanisms of SC failures. Many case histories have reported SC failures in external

exposure environments, but most do not involve failure of the SC itself. Failures are most often associated with peeling off of sound SC from the substrate to which it was applied. The causes of such failures include:

(1) inadequate preparation of the substrate surface, (2) application of a thin layer of SC to nondurable base concrete, (3) failure to provide adequate drainage and pressure relief, and (4) failure to adequately prepare the face of an existing SC layer prior to application of the next layer (particularly important for latex modified SC). Recommendations for producing durable SC in the field include: (1) use of nonsusceptible aggregates, (2) use of experienced nozzle operators for quality workmanship, (3) use of high cement content, low W/C ratio, and air entrainment (in wet-mix process), (4) use of strength testing as a quality guideline for durability (noting that strength is not an absolute guarantee of durability), (5) adjustment of the spacing factor, (6) use of preconstruction testing with the actual crew and materials, and (7) use of laboratory freeze-thaw testing (either ASTM C671 or ASTM C666).

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-035

AUTHOR(S): Reading, T. J.

PAPER TITLE: Durability of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 3, Number 1

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: January, 1981

PAGES (papers): pp. 27-33

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author presents data from 4 different projects by the US Army Corps of Engineers. Six different mixtures were evaluated by ASTM C666, Procedure A, with 4 of the 6 mixes receiving a poor rating. Specimens were also tested by field exposure at the Corps of Engineers exposure plot at Treat Island, Maine. For a structure with 100 year design life, a 10 year specimen life at Treat Island is desired. Only one specimen had a specimen life of less than 7 years at Treat Island, and 2 specimens had specimen life greater than 10 years. The conclusion was that it is possible to produce both dry-mix and wet-mix process SC which will survive freeze-thaw conditions. ASTM C666, Procedure A appears to be even more severe than some of the harshest freeze-thaw conditions existing

in nature, and results from this test should be interpreted with caution.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH03-036

AUTHOR(S): Schrader, E. and Kaden, R.

PAPER TITLE: Durability of Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Durability

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-100

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1987

PAGES (papers): pp. 1071-1101 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The authors reported results from 13 different Corps of Engineers projects. The general conclusion was that dry-mix SC is not durable for freeze-thaw conditions. Of 20 mixes, only 4 rated excellent for freeze-thaw durability. Two of the four mixes with excellent rating were latex modified and the other two had the following beneficial factors: (1) 5% air content in the hardened concrete, (2) excellent spacing factor (0.003 in.), and (3) high strength (CS > 7 ksi at 28 days). Reported durability for wet-mix SC was better than for dry-mix SC, with air entrainment appearing to be a significant factor in the durability tests. However, only about 1/3 of the wet-mix SCs tested achieved an excellent rating.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-001

AUTHOR(S): Kahn, L. F.

PAPER TITLE: Shotcrete Strengthening of Brick Masonry Walls

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 6, Number 7

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: July, 1984

PAGES (papers): pp.34-40

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC is presented as a method of reducing seismic risk in older, unreinforced masonry structures. The most widely used method for seismic strengthening is the application of a layer of reinforced SC to one face of unreinforced masonry walls. Design is based on the assumption that the existing brick carries the existing dead load, and that the SC walls carry all lateral loads. Research involved both the brick-SC composite behavior and also a lower cost method using thin SC layers as a retrofit technique for areas of moderate seismicity. Panel tests for ultimate strength indicated up to 1700% increase in strength compared to the control (brick alone) panel. Even with minimal reinforcement, inelastic and reversed cycle deformation was possible. Light reinforcement with expanded metal combined with a thin SC layer provided

significant strengthening, and is recommended as a technique for areas of moderate seismic risk.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-002

AUTHOR(S): Webster, R. P. and Kukacka, L. E.

PAPER TITLE: In Situ Repair of Deteriorated Concrete in Hydraulic
Structures: Feasibility Studies

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Technical Report REMR-CS-6

CORPORATE AUTHOR OR PUBLISHER: Process Sciences Division,
Brookhaven National Laboratory,
Upton, New York

MONITORING AGENCY: Structures Laboratory, US Army Engineer
Waterways Experiment Station, Vicksburg,
Mississippi

PUBLICATION DATE: May, 1987

PAGES (papers): -0- TOTAL PAGES (books): 80

DISCUSSION: -0-

KEYWORDS: concrete, cracking, hydraulic structures, in situ
repair, polymer impregnation, post reinforcement,
pressure injection, spalling

REVIEW: Twelve methods for crack repair are detailed, based on a
report (1984) by ACI Committee 224. Shotcreting is
presented as 1 of 7 methods to repair concrete spalls.
Wet and dry processes are mentioned. Dry process SC
allows the nozzle operator to vary the consistency of the
SC to fit the specific needs of a particular area.
However, the dry process requires an experienced nozzle
operator. Expansive, latex-modified, and polymer

concretes are mentioned as repair materials along with conventional materials such as bituminous coatings, PCC, grout, and epoxies. Use of SC to repair surfaces may require reinforcing to reduce the possibility of reflective cracking. Polymer grids are suggested as a low cost reinforcement to reduce reflective cracking.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-003

AUTHOR(S): Webster, R. P. and Kukacka, L. E.

PAPER TITLE: In Situ Repair of Deteriorated Concrete in Hydraulic
Structures Laboratory Study

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Technical Report REMR-CS-11

CORPORATE AUTHOR OR PUBLISHER: Process Sciences Division,
Brookhaven National Laboratory,
Upton, New York

MONITORING AGENCY: Structures Laboratory, US Army Engineer
Waterways Experiment Station, Vicksburg,
Mississippi

PUBLICATION DATE: January, 1988

PAGES (papers): -0- TOTAL PAGES (books): 34

DISCUSSION: -0-

KEYWORDS: concrete, cracking, hydraulic structures, in situ
repair, polymer impregnation, pressure injection,
spalling

REVIEW: Shotcrete is not addressed in this report. Pressure
injection and polymer impregnation techniques are
discussed.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-004

AUTHOR(S): McDonald, J. E.

PAPER TITLE: Rehabilitation of Navigation Lock Walls: Case
Histories

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: -0-

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Technical Report REMR-CS-13

CORPORATE AUTHOR OR PUBLISHER: Structures Laboratory, US Army
Waterways Experiment Station,
Vicksburg, Mississippi

MONITORING AGENCY: -0-

PUBLICATION DATE: December, 1987

PAGES (papers): -0-

TOTAL PAGES (books): 316

DISCUSSION: -0-

KEYWORDS: concrete, concrete removal, durability, navigation
locks, rehabilitation, repair

REVIEW: Bids for the Marseilles Lock repair on the Illinois
Waterway showed that SC was the lowest cost alternative.
However, concerns about QA led to the use of formed
concrete at a higher cost. SC (Gunitite) was used for
resurfacing at the Dresden Island Lock and Dam near
Morris, Illinois. Borings indicated that the SC provided
excellent bonding with the original concrete. Air-void
data indicated that the SC was useful for frost
resistance. In some areas, shotcrete was placed to
repair weathered surfaces in 1954. In general, the SC
was in excellent condition after more than 30 years in

service. Low marks were given to SC in a repair at Lock No. 3 on the Monongahela River near Elizabeth, Pennsylvania. These reports seem unfair, however. For example, a river wall Gunited in 1940 was reported as "completely deteriorated" after only 38 years in service. Also, the performance of thin layers (less than 1/2 inch) over smooth surfaces was unsatisfactory when exposed to severe impact and abrasion by tows. Reflective cracking of shotcrete overlays did seem to be a legitimate area for concern, with some cracks and spalls requiring special caulking. Cracking was a much worse problem in conventional repairs using formed concrete at Lock No. 1 on the Mississippi River, near St. Paul, Minnesota. SC was used on the Lower Monumental Lock on the Snake River, near Pasco, Washington. Laboratory testing indicated that a resurfacing with fiberglass fiber-reinforced latex-modified shotcrete mix would meet design requirements. Six mixtures were used in a demonstration which indicated that proper surface preparation was essential for bonding and that a careful benefit/cost evaluation should be used to determine the preferred mix design. Debonding has continued to be a repair problem, with an estimated 15-20% debonding of the latex-modified, fiber-reinforced SC after 6 years. SFRS (Fibercrete) was used at the Emsworth Locks near Pittsburgh, Pennsylvania. Subsequent inspections led to the conclusion that the SC exterior coating had contributed to freeze-thaw deterioration of the underlying concrete. In general, the SC performed well, but reflective cracking was a localized problem in some areas. Several other case histories were detailed which used conventional repair techniques. In all cases, for all techniques, cracking was a problem. In general, SC was found to be economical for resurfacing of less than 12 inches thickness. Debonding was a problem for SC surfaces, but was most often due to the freeze-thaw deterioration of underlying materials which was exacerbated by the low permeability of the SC. Freeze-thaw was not a serious problem within the SC. When the thickness of SC was greater than the depth of frost penetration, debonding was not a problem, with some areas in excellent condition after more than 30 years service. Standard SC has not performed well in thin overlays. SFRS did not perform well, but may have been due to low fiber content (only 60 lb/cu yd instead of up to 200 lb/cu yd). Fiber-reinforced, latex-modified

SC performed satisfactorily only when surface treatment was adequate.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-005

AUTHOR(S): Bell, R. A.

PAPER TITLE: Shotcrete Restoration of a Historic Landmark

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 19, Number 4

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: April 1974

PAGES (papers): pp. 161-163 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Describes shotcrete restoration of the Unity Temple in Oak Park, Illinois. The building was one of the early (1906) structures made with reinforced concrete, and used an exposed pea gravel finish for a unique surface texture (designed by Frank Lloyd Wright). Several structural rehabilitation techniques had been used to correct extensive cracking, spalling, and water penetration. The corrective measures arrested deterioration, but lost the original color and texture of the building. An area which had been covered with copper was revealed in 1970, and a restoration effort was undertaken with Lloyd Wright (oldest son of Frank Lloyd Wright) acting as the principal consulting architect. Pea gravel was located which was similar to the original mix. The surface was etched with an abrasive blast using power house slag

blasting grit. The new coating was pneumatically applied in a thickness of about 1/2 to 3/4 inches thick. Special care was used to finish the surface, and the new surface could hardly be distinguished from the original texture. Special forms were used to provide square corners, and were done in a "patchwork" manner.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-006

AUTHOR(S): Gilbride, P., Morgan, D. R., and Bremner, T. W.

PAPER TITLE: Deterioration and Rehabilitation of Berth Faces in
Tidal Zones at the Port of Saint John

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Second International Conference
on Performance of Concrete in Marine
Environment

DESCRIPTIVE BOOK NOTE OR EDITOR: St. Andrews, NB, Canada

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-109

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1988

PAGES (papers): pp. 199-226

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: concrete durability, deterioration, fiber reinforced
concretes, freeze-thaw durability, marine atmospheres,
repairs, shotcrete, silica fume, tests, wharves

REVIEW: The paper describes a case study of marine structural
repair. The berth faces (wharves) had deteriorated due
to freeze-thaw, alkali-aggregate reaction, and marine
salt reaction. The repair method used wet-mix, steel
fiber reinforced, silica fume SC, anchored with grouted
dowels. This method provided a thick veneer of dense
impermeable concrete over an essentially weak and
permeable concrete base. Restrained drying shrinkage
cracks occurred in the surface after about 1 years

service, but were not considered a serious problem. A sealing coat of SC was applied to protect the underlying concrete from any intrusion of marine material. The authors anticipate maintenance operations during each new construction season.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-007

AUTHOR(S): Ramakrishnan, V.

PAPER TITLE: The Role of Superplasticized Fiber Reinforced
Concrete and Fiber Shotcrete in the Rehabilitation
of Bridges

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, International Conference on
Rehabilitation of Buildings and Bridges,
Including Investigations

DESCRIPTIVE BOOK NOTE OR EDITOR: Bombay, India, December 21-23,
1981

VOLUME & NUMBER OR REPORT NUMBER: -0-

CORPORATE AUTHOR OR PUBLISHER: National Science Foundation,
Washington, DC, USA

MONITORING AGENCY: -0-

PUBLICATION DATE: 1981

PAGES (papers): pp. 101-108 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Much of this paper concerns the improved properties which
were achieved with superplasticized steel fiber concrete.
However, the mixture was applied as a SC mix, and this is
briefly summarized. The following comments are quoted
from the text: "The addition of steel fibers to SC makes
it almost an ideal material for concrete repair and
renovation." "... steel fibers make SC a tenacious
material." "Steel fiber SC resists far greater impact
and shock ... than plain SC." "Because of its increased

resistance to blasts and shocks, ... fiber SC is highly recommended for military structures." Existing equipment with little or no modifications can be used for the application of steel fiber SC, when special fibers are used. These have deformed ends and are glued together to reduce the "balling" typically reported for these mixes.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-008

AUTHOR(S): Hurd, M. K.

PAPER TITLE: Structural Rehabilitation of Concrete Lighthouse

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 33, Number 7

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: July, 1988

PAGES (papers): pp. 659-663

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The Brandywine Shoal Lighthouse was the first reinforced concrete structure of its kind located on a submarine site in the continental United States. Rehabilitation was needed due to deterioration from the harsh marine environment which included freeze-thaw action as well as reinforcement corrosion. A combination of pre-cast slabs and thick steel plates were used to provide the structural support, with SC used as an outer sealing material including sealing of the steel welds. Repairs were completed in March, 1987, and won an award from the Prestressed Concrete Institute.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-009

AUTHOR(S): Schoenberner, R. A.

PAPER TITLE: Down the Hole

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 33, Number 1

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: January, 1988

PAGES (papers): pp. 18-19

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A hard to access wall repair (a square access hole had 2.5 foot sides) is documented. The walls of a powerhouse sump had deteriorated due to chemical penetration. Waterblasting followed by sandblasting was used to prepare surfaces. Precut section of wire mesh were installed to control temperature and shrinkage cracking. Dry-mix shotcrete was applied, with dry-mix process used because of the ease of material conveyance. The nozzle operator gave instructions to the mixing rig operator via a two-way radio. Another worker equipped with an air wand removed rebound inclusions so that the nozzle operator could apply a sound, dense material. A high early and final strength mix was used, with 1-day strengths between 6000 and 8000 psi. The low permeability provided resistance to chemical penetration. The final SC surface

was sandblasted and coated with a silica-filled lining. The entire restoration was completed in 2 weeks. The success of this method has led to the repair of 8 sumps in the last 7 years.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-010

AUTHOR(S): Fluss, P. J. and Gibson, G. E.

PAPER TITLE: Shotcrete Repairs on Waterfront Substructures

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 85-92

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case study is presented of repairs on piers and bulkhead wharves of the Port of San Francisco. The project required that the piers be kept open and the work be done within the tidal range of the San Francisco Bay (variation up to 6.5 feet). Scheduling was critical, with much of the work done at night. The thickness of SC placed varied from about 1.5 to 8 inches, with an average of about 4 inches. Special attention was given to: (1) eliminating hollow pockets behind reinforcing steel, (2) removal of rebound, and (3) elimination of sagging (checked visually and by the steel wire fabric). Mix used was 1:3.5 by volume. A protective asphalt coating was used to enhance curing and corrosion protection.

The asphalt coating can extend the life of the SC in the splash zone to almost double. Panel tests were used for strengths, with strengths in the 5 to 7 ksi range. Sounding was used to locate voids. The cost was much less than for other repair methods due to the problem of difficult access.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-011

AUTHOR(S): Dykmans, M. J.

PAPER TITLE: Shotcreting of Prestressed Concrete Tanks

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 99-108

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Use of SC for this application is typically a matter of economics. This can be done effectively, but several special construction techniques must be employed for these structures, particularly to ensure proper coating of reinforcing steel and sealing of joints. In addition, curing is important. Use of epoxy-vinyl, vinyl-latex, or rubber-base paint coatings after normal curing procedures is recommended to ensure long-term strength gain. Wind is mentioned as a problem, with materials being carried away by wind. The SC should be shot against the wind to avoid working in rebound carried by the wind. Use of plywood screens on each side of the nozzle operator will usually allow placement. Admixtures may increase

corrosion in water tanks. Use of high cement contents is suggested to decrease permeability and maintain high pH for decreased corrosion.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-012

AUTHOR(S): Crowley, F. X.

PAPER TITLE: Prestressed Shotcrete-Steel Diaphragm Tanks

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 109-122

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: History and developments for these structures are discussed. The entire construction sequence is described. Of particular interest are four fundamental rules for SC over prestressed wire. These are: (1) bondable surface, (2) wire spacing for placement between wires, (3) SC cover coat of good quality, and (4) minimum of 3/4 inch cover for each wire. Painting has been used to provide uniform color. Testing was made by cubes from a 12x12x3 inch test panel. Shooting into a hardware cloth cylinder is also discussed as an acceptable method.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-013

AUTHOR(S): Tinsley, E. C. and Kalousek, H. L.

PAPER TITLE: Pneumatic Gunning of Refractory Castables

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 139-154

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: For these structures, the dry-mix process is favored. Skill of the crew is discussed as an important factor. Predampening of the dry mix improves the uniformity of the mix. Equipment is discussed, particularly differences in nozzle tips. Three main types are the balloon-type tip, the modified tip, and the straight-type tip. Variations in density are discussed as a problem for these structures. Typical properties are tabulated. Several points for job planning are: (1) locate guns conveniently, (2) be sure adequate air and water are available, (3) plan premixing facilities to charge guns efficiently, (4) provide adequate scaffolding, (5) have spare parts on hand, (6) have

surface clean and ready for gunning, and (7) store materials near the site. In addition to mix proportioning and curing, the following important details were discussed: (1) the mix should have enough coarse aggregate to give in-place strength, prevent slumping, and feed properly, (2) too coarse mixes may have excessive rebound (use pneumatic extrusion for wet-mix), (3) very fine-grained material may generate dust and create laminations, (4) predampening and mixing can improve gunability, (5) reduced gunning pressure usually lowers the bulk density, and (6) the nozzle should be at 90 degrees to the surface at a distance of 3 to 4 feet.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-014

AUTHOR(S): Crawford, J. P.

PAPER TITLE: Shotcrete for Structural Rehabilitation

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 367-404

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Several case studies are included which focus on SC for structural rehabilitation. At the Hanna Tunnel, at Cadiz, Ohio, the original lining of concrete, brick, and steel mine arches had shifted during the lowering of the roadbed to accommodate "piggyback" operations for automobile transportation. The shifting and subsequent icing conditions caused excessive deterioration of the lining. A repair consisted of: (1) rock bolting of the crown, (2) removal of deteriorated concrete,

(3) installation of wire mesh, (4) scale, chip, and clean all surfaces to prepare a bondable surface, (5) apply smoothing SC to areas of deep spalling, (6) installation of water control piping, (7) application of structural SC lining, (8) grouting of portions of the walls, and (9) adjustment of drainage control to conform with conditions of leakage after grouting. At the Rexford Tunnel, at Rexford, Ohio, the tunnel was driven bald and remained unlined for many years. In 1947 and again in 1954, gunite with wire mesh was placed on the tunnel walls. The gunite ranged in thickness from 6 to 8 inches. A shear occurred in the tunnel and the gunite tore from the walls in many places, causing the tunnel to take on water. The tunnel was considered in a state of imminent collapse. The repair consisted of: (1) secure the tunnel by support bars over the crown, (2) removal of old gunite and replacement with SC, (3) repair concrete portal structure and walls by removing old concrete and replacing with SC-rock bolt system, (4) remove deteriorated concrete pilasters and rebuild with SC, (5) reconstruct drain gutters, and (6) remove debris from site. At the Detroit Water Tunnel, under Lake Huron, a methane gas explosion caused extensive damage. Over 200 cubic yards of SC were needed to complete the repairs. Repair dimension and specifications are included.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-015

AUTHOR(S): Kaneshiro, J. Y.

PAPER TITLE: Shotcrete Wine Storage Caves

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: -0-

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: -0-

PAGES (papers): pp. 42-44

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Reinforced concrete, shotcrete, subsurface structures,
storage, tunnels

REVIEW: Case history of storage facilities constructed at
Saratoga-Skyline Vineyard, near the San Andreas fault at
Saratoga, California. The caverns are reinforced
concrete structures using the Bernold forming and
reinforcing system (designed for alpine tunneling). The
Bernold system uses interlocking steel plates of 1.1x1.2
meters (3.5x4 feet) which weigh about 20 Kg (45 lb) each.
The plates are assembled into a framework and then
covered with shotcrete, without using conventional
plywood formwork. Design utilized a spreadsheet program
to compute moments, shears, and axial loads which were
subsequently used for design by strength methods and the
ACI-318 code. Seismic design incorporated pseudo-static

methods but did not preclude damage to the caves during a maximum credible earthquake. The Bernold plates and bracing were erected and shot with SC. After 28 days, the caves were backfilled with a minimum of 1.8 m (6 feet) of fill to provide a constant temperature environment within the caves. The project was completed within 3.5 months, prior to the fall harvest. The total project costs amounted to about \$75 per square foot of cave area.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-016

AUTHOR(S): Abdel-Halim, M. A. H. and Schorn, H.

PAPER TITLE: Strength Evaluation of Shotcrete-Repaired Beams

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: ACI Structural Journal

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 86, Number 3

CORPORATE AUTHOR OR PUBLISHER: American Concrete International,
Detroit, Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: May-June, 1989

PAGES (papers): pp. 272-276

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Beams, supports, cracking, fracturing, deflection,
performance, reinforced concrete, repairs, shotcrete,
strength, tests

REVIEW: Beams were spalled and repaired with shotcrete in full-scale tests. The deflection behavior of repaired beams was no worse than for original beams up to the first yielding of the steel. For loading higher than first yielding, the repaired beams had more deflection. There was no difference in load-deflection curves for normal SC and polymer-PCC SC. The repaired beams had strength reduction of 8% and 12.5% for replacement of 20 mm and 35 mm, respectively. Cracking patterns for the repaired beams were similar to cracking patterns in original beams, with no debonding at the interface with parent material. Conclusions of the study included:

(1) repair of cracked tension zones by removal/replacement with SC is a successful technique, (2) strength reduction was 8% and 12.5% for removal/replacement of 20 mm and 35 mm of original material, respectively, (3) maximum crack widths were larger in the repaired beams than in the original beams, (4) crack patterns and modes of failure were similar for the repaired and original beams, (5) normal SC as well as polymer-PCC SC can be used for these repairs, with little difference in behavior, and (6) the SC layers and parent material acted compositely throughout loading to failure.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-017

AUTHOR(S): Rebull, P. M. and Gutierrez, R. G.

PAPER TITLE: Full-Scale Test of Shotcrete for Permanent Tunnel
Lining in Clay

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 400-404

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A significant part of the cost of sewer construction is the cost of temporary support required to construct the permanent lining of the conduit. The use of SC for temporary ground support has been accepted in Europe and in limited cases, in the Americas. Engineering properties of the clay were considered in the design process. A nominal 4 inch thickness of SC was applied after each advance of 1 radius (4 feet). CS of 1860 psi

were achieved in 24 hours, and a good bond to the clay and low rebound were achieved. Numerous Gloetzl pressure cells were installed and closure measurements were taken of ground and lining deflection. The data showed that stability was achieved in several days, and that the pressure buildup has remained essentially constant since the structure was built in 1970. Pressures on the lining stabilized at about 1/3 of the overburden vertical stress, and tangential compressive stresses in the concrete equilibrated at about 200 to 300 psi.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH04-018

AUTHOR(S): Ruffert, G.

PAPER TITLE: Shotcrete for Repairing and Reinforcing Bearing
Concrete Structures

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Beton

DESCRIPTIVE BOOK NOTE OR EDITOR: Herstellung, Verwendung

VOLUME & NUMBER OR REPORT NUMBER: Volume 36, Number 2

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: February, 1986

PAGES (papers): pp. 53-55

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Buildings, repair, structural design, safety factor,
concrete construction, shotcreting, personnel training

REVIEW: Review consisted of detailed abstract written in English, with the actual reference written in German. The author states that the shotcrete method can be considered as perfected, based on more than 60 years of experience with the application of SC for reinforcing and repairing of reinforced concrete structures. The existing technical regulations based on that experience and a great number of fundamental tests are used as evidence to support his conclusion. Use of technical regulations alone is not adequate to ensure quality when the SC method is applied to the repair of bearing structures, because steps must be taken to insure that personnel have the special training needed. Only by combining regulations with

skilled personnel will the quality standard be the same in the repair and reinforcing of structures with SC as for new buildings.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-001

AUTHOR(S): Bills, R. F.

PAPER TITLE: Shotcrete as an Integral Part of Shaft Construction

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 201-210

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC was substituted for rock bolting when a cave-in in similar ground was reported. SC work was completed with a two-man crew on pot and nozzle. The biggest problem on this job was scheduling, since one crew was responsible for multiple shafts. NOTE: A similar scheduling problem could occur if SC is used for expedient repair on USAF bases. Wet process was used. Results were good, with core strengths of 2500-3500 psi and no appreciable movement of the liner walls. The major advantage of SC noted was the shaft support. Other minor advantages

noted included canalization of ground water to weep pipes and a light colored surface which was easy to illuminate. SC was credited for an excellent safety record compared to similar shafts which were bolted and chain linked. Safety problems which were avoided related to falling, sloughed, or loosened material.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-002

AUTHOR(S): Rogers, E. R.

PAPER TITLE: Developments in Shotcrete Equipment

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 211-224

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper addressed: (1) Shotcrete machines (guns), (2) Delivery systems, and (3) Accessories. Only high velocity placement will achieve the densities and strengths required in engineering applications of SC. Pneumatic conveyance is recommended. Dry-mix process is recommended because W/C ratio is lower and the reaction on water and cement begins later in the process. A shotcrete machine is a mechanism to meter a granular material into an airstream. The most popular SC machine is the "Reed Guncrete" machine developed in 1960 by

Frank Reed. The system uses a feed bowl with cavities at the bottom. A circular sealing plate covering 20% of the cavities at a time rotates, and the material is forced out of the cavities by compressed air. The rotating plate provides a smooth feed. Machines are available which drop material into a lower pressure air stream, but these machines are not recommended by the author. Several "advertisements" for Reed Manufacturing Company are made by the author. Prehydration of the cement will dramatically reduce the in-place strengths of SC. However, the use of "bone-dry" mixes can cause excessive dusting and rebounding. Use of a secondary water ring is recommended as well as predampening. Use of a "Reed-Mate" predampening device is recommended. Use of fiber-reinforced mixes to support wide span flat roofs in coal mines is possible because of the high tensile strength of the resulting material. Steel pipes have been used to deliver the dry SC mix to the nozzle. A spinning nozzle has been used to reline furnaces in steel mills. Low voltage electrical control devices enable the nozzle operator to control gun functions.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-003

AUTHOR(S): Monaghan, D. A., Hoadley, D. J., and Anderson, G. L.

PAPER TITLE: Remote Shotcrete Lining of Raised Shafts

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 225-240

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The system allowed complete remote control of SC nozzle operation using a thickness gage and video monitoring system. Dry process was used because of long pumping distances. The dry process permits accelerators to be added at the nozzle, avoids pumping of wet concrete, minimizes line plugging, lowers W/C ratio, and reduces hydration during transport. Remote control of the rotary SC system allows the operator to control the rate of descent; rate and direction of rotation; attitude of nozzle; and flow rates of shotcrete, accelerator, and

water. Required equipment was a "Concrete Mobile" to deliver the mix, a shotcrete machine to meter and inject the shotcrete mix (as well as screening the oversize aggregate), hoses to convey the mix, water pumping system, electrical cable and water hose reels, a headsheave support system, a winch and drum system to spool the wire rope supporting the SC assembly, and an operator control console. Operation of the entire system required only three people (one each for the control system, the SC machine, and the Concrete Mobile). A case study was presented. In general, 5 to 6 inch linings were placed satisfactorily. In water bearing areas this method failed, and the following method was used successfully: (1) the wet zones were sandblasted, (2) a 1 inch thick flash coat with 4% accelerator was applied, and (3) the lining was completed using standard SC. Cores showed good CS. Material loss to rebound was about 25%. The demonstration study showed a cost savings of almost 25% with a tripling of production rate and improved safety. Attention is called to legislation in some states which does not allow workers in unsupported areas, and remotely applied SC is proposed as an economical answer to this safety problem.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-004

AUTHOR(S): Egger, H. R.

PAPER TITLE: Shotcrete: Wet or Dry Process

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 241-249

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Three methods of transporting a shotcrete suspension are currently in use: (1) transport of dry aggregate in a stream of air, (2) transport of slugs of wet mix by compressed air, and (3) mechanical transport of compact wet mix. Method 1 (the classical method) has been criticized, particularly for dust production, uncontrolled water dosage, and low output. Method 2 seeks to reduce rebound. Method 3 allows good control of water dosage. Method 2 can cause clogging of lines. Method 3 requires a higher W/C ratio and gives less compaction energy,

although the rebound is much lower. Method 1 can produce the best quality concrete, and can be used with accelerators. Pre-humidification and/or premix nozzles have practically eliminated the dust problem. Dust at the machine can be eliminated with a dust collector. The premix nozzle is recommended because of the homogeneity of the resulting SC. Organic liquid accelerators are recommended, and should be dispensed with a dosage pump. A good nozzle operator uses his eyes to vary the dosage within narrow limits. Outputs of 7 cubic yards per hour are possible with Method 1. Important features of Method 1 are: (1) use of fresh mix (no prehydration), (2) high impact energy (higher ultimate strength and better bonding), and (3) more flexible for scheduling (don't have to continue until "batch" is finished).

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-005

AUTHOR(S): Packham, G. R.

PAPER TITLE: Shotcrete Equipment

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 250-253

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Three systems noted: (1) dry process, (2) wet process, and (3) compressed flow process. This paper deals only with dry process. Rotary feed machine is recommended because of continuous production, variable nozzle output, and ease of operation and maintenance. A suitable feeding machine is needed. Hand feeding of materials is not recommended. Mobility of the system is important. Use of a truck feeding system is mentioned, as is a combination of truck to hopper-type feeding systems. Communication between crew members can usually be done

with hand signals, but can also be done by radio.
Addition of accelerators should be as late as possible in
the delivery process to avoid premature hydration.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-006

AUTHOR(S): Alberts, C. and Kramers, M.

PAPER TITLE: Swedish Shotcrete Equipment and Developments in
Fibrous Shotcrete

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 254-268

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Remote application is described, using an extendible robot arm to control the nozzle. The robot arm has its own hydraulic system, so it can be easily moved between carrying systems. The basic sweeping motion has been automated, so the operator is free to concentrate on other things. A platform mount will allow lateral movement of the system. The operator can leave the machine and control the arm with a small control box. Robot spraying has been combined with tunnel boring

machines. The major advantage for tunnel excavation is that operations can begin earlier without safety problems. Advantage of the operator is less direct labor and also avoiding a shower of rebound. The operator can therefore concentrate on dispensing a quality mix. A "Triker" is recommended for premixing the dry mix. Humidity can start prehydration in dry mixes which are transported. They carry components separately and mix on site for freshness. Liquid accelerators are recommended. A proportioning pump should be used to premix the liquid accelerator with the mix water. Use of steel fiber reinforced SC was satisfactory, but requires a fiber proportioning and dispensing unit. Fiber reinforced SC can be delivered by the robot system. Laboratory studies indicated the best fiber was wavy, 20 mm long, and had a diameter of 0.35 mm. Tensile strength and flexural strength were increased by 50% and 180%, respectively. CS was also improved. The application rate for the above tests was 2.3% by volume, but because of rebound the actual content was 1.34% by volume. The fiber reinforced SC has high tensile strength with good flexibility (low cracking) and is therefore recommended for temporary reinforcement and for use as a protective coating to prevent flow of water and/or gases.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-007

AUTHOR(S): Crom, T. R.

PAPER TITLE: Dry Mix Shotcrete Nozzling

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete International, Design and
Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 3, Number 1

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: January, 1981

PAGES (papers): pp. 80-93

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: aggregates, compressive strength, concrete
construction, curing, finishes, mixing, mix
proportioning, shotcrete

REVIEW: "Slugging" delivery systems will create poorly hydrated SC. Continuous flow systems should be used. Equipment setup should be planned so that SC can be delivered uniformly. Nozzle operator should be able to move close enough to shoot rebar but far enough away to avoid rebound. Finer sand is easier to finish, but can lead to equipment clogging. Delivery techniques for the nozzle operator are described which minimize the creation of sandpockets from rebound and overspray. It is important to keep the nozzle square or radial to the wall and to keep the nozzle moving about the work area. Sound SC should have 100% bond with bondable material. This can be achieved

if surface is prepared properly. Rebound and overspray material should be cleaned by the nozzle operator using compressed air. An assistant can help the nozzle operator to keep the nozzle at a good angle. Care must be taken to encase reinforcing steel. The SC must be built up behind the rebar by shooting from each side so that sandpockets do not develop due to segregation. Overspray around rebar should be cleaned off before final set to assure encasement. Air pipes are not recommended for the removal of overspray, but an air-water blast from the nozzle will work. Also, the surface can be finished by hand to remove overspray. Vibration of rebar from SC application can cause flow and/or sagging which can lead to cracking. Steel should be tied rigidly. Joints are usually not used in SC, but if they are included for design purposes, care must be used to keep them free of rebound material. When applying multiple layers, let each layer get initial set, clean surface, and do not apply curing compounds (which act as bond-breakers). Repair of defects is discussed, with removal/replacement of poor material as the primary method. SC is most economical for thin, lightly reinforced applications. SC should not be used to fill narrow slots or deep holes. These should be filled by conventional dry-packing, then overlaid with SC. Natural gun finishing is preferred from a structural and durability standpoint. Special curing considerations may be needed for wet process SC, particularly in areas of temperature extremes. Rain may damage exposed fresh SC. Strong winds can separate SC materials during placement, so that wind shields may be necessary.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-008

AUTHOR(S): Nicholls, R. and Freeman, J.

PAPER TITLE: Buckling of Fabric-Reinforced Concrete Shells

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Journal of Structural Engineering

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 114, Number 4

CORPORATE AUTHOR OR PUBLISHER: American Society of Civil
Engineers

MONITORING AGENCY: -0-

PUBLICATION DATE: April, 1988

PAGES (papers): pp. 765-782 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: buckling, concrete construction, cracking (fracturing),
deflection, ductility, fabric, flexural strength,
lightweight aggregates, reinforced concrete, shotcrete

REVIEW: Paper does not address SC directly. A shell may be
created by inflating cement treated fabric-reinforced
shells and wetting them down. Design is discussed.
Compared with SC on inflated forms, the costs are less
but quality varies widely.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-009

AUTHOR(S): Hurd, M. K.

PAPER TITLE: Bridges and Culverts Shotcreted Over Inflated Forms

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 33, Number 4

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: April, 1988

PAGES (papers): pp. 385-388

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: arches, bridges (structures), culverts, forming techniques, formwork (construction), inflatable structures, shotcrete, structural design

REVIEW: Inflatable forms can be used 40 to 50 times each, and can be adapted to many shapes by using steel strapping for restraint. The steps are: (1) tie down and inflate the forms, (2) set support bolsters and place rebar, (3) apply SC up to 6 inches in a layer, and (4) deflate the form. Several cases are mentioned where the inflatable forms have resulted in big cost savings during construction. Forms can be rented or leased as well as purchased.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-010

AUTHOR(S): -0-

PAPER TITLE: Air-Inflated Forms Cut Cost of Drainage Structure

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Public Works

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 118, Number 7

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: July, 1987

PAGES (papers): pp. 45-47

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case study is described where SC over air-inflated forms provided a sound, economical solution to a drainage problem with logistic and construction difficulties for conventional designs.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-011

AUTHOR(S): Wilson, F. C.

PAPER TITLE: Ball-valve Concrete Pumps

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Concrete Construction

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: Volume 33, Number 2

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: February, 1988

PAGES (papers): pp. 145-148

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Ball-valve pumps have been used for low volume pumping, but are now being used for more demanding jobs. The valve system is driven by a cam and is controlled entirely by the flow of concrete. On the intake cycle, the cam moves back, and the backward flow closes the discharge cylinder and draws in concrete from the feed hopper. On the discharge cycle, the cam moves forward, pushing the ball on the feed hopper into a closed position and pushes open the discharge cylinder, allowing the outward flow. A cleanout port allows the removal of oversize material. Some hydraulically driven ball-valve pumps have pumped structural concrete at outputs exceeding 150 cubic yards per hour, although (slower) mechanical pumps are also commonly used. Because small diameter aggregate is used and the volume is relatively

low, small diameter lines and hoses can be utilized, with maximum pressures from 300 to 900 psi (most jobs require only 100 to 150 psi). These pumps perform better for uniform mixes. These pumps have few safety problems when concrete discharges freely and the lines are not excessively long, although bursting can occur in lines if flow is blocked.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-012

AUTHOR(S): Fredericks, J. C., Saunders, N. R., and Broadfoot, J. T.

PAPER TITLE: Recent Developments in Positive Displacement
Shotcrete Equipment

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 75-84

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Two relatively new methods for delivering wet-mix SC are presented. One is a squeeze pump and the other is a piston pump. The rotating roller squeeze pump can deliver up to 12 cubic yards per hour, with discharge hose length of up to about 100 feet for stiff mixes. Discharge hose lengths of 200 feet have been achieved by injecting compressed air in the hose. The piston pump can be pumped up to 200 feet at a rate of 12 to 20 cubic yards per hour. Mix designs for both pump types are discussed, with slump in the ranges of 1/2 to 2 inches possible. Actual field uses are discussed. It is

concluded that this equipment will be utilized more in the future because it can deliver low-slump wet-mix process SC at a high delivery rate and the wet-mix process SC has several inherent advantages.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-013

AUTHOR(S): Alberts, C.

PAPER TITLE: Use of Remote Controlled Spraying Nozzle

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 65-78

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The ROBOT method was developed during construction of a power plant in Sweden. (REVIEWER'S NOTE: Much of the information in this paper has been reported in a previous review of a later paper, and is quickly summarized here.) Equipment discussed herein includes the TRIKEX (combined transportation-mixing unit), the STABILO PUMP (for liquid accelerators), and the ROBOT TRIKEX. The material capacity for the ROBOT TRIKEX is 3.6 cubic yards. The

nominal mixing capacity is 7 cubic yards per hour. The unit can travel at 11 mph.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-014

AUTHOR(S): Valencia, F. E.

PAPER TITLE: Practical Aspects of Shotcrete Application

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 114-129

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: For tunnel linings, some practical aspects must be considered in addition to the usual requirements of uniform delivery and proper proportioning of SC. This includes proper control of water during shooting to minimize dusting and rebound and to maximum bonding. Effective cleaning of rock surfaces is essential for good bonding. Also, proper spraying techniques are required to assure a competent finished product. Important points for equipment are: (1) a good consistent maintenance

program is cost effective, (2) sufficient clean compressed air is necessary to minimize fluctuations in the material delivery stream, (3) the pressure should not be excessive (40 to 45 psi for 100 feet of 2 inch hose) so that the nozzle can be held horizontally (with one hand) with the arm extended vertically overhead, (4) the air stream must be free of oil (can be checked by passing the air from the nozzle into a bucket of water and looking for oil film in water). A common fault of nozzle operators is to move too far from the point of impact, making it harder to monitor his own work, and may leave voids in fractured rock faces. Use a normally oriented spray at about 18 inches (acceptable range is 6 inches to 3 feet) from the rock face to establish a line of stability with all recesses filled. A steady systematic clockwise motion is preferred. Testing with various nozzles showed that a double ring provided more uniform mixing and that slotted water ports were more efficient in providing uniform wetting than the more standard rounded ports. The double water ring requires special high pressure systems, but another system which can improve wetting uses two single (standard) water rings, placing one ring at about 5 to 10 feet from the nozzle water ring.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-015

AUTHOR(S): Goff, J. S.

PAPER TITLE: Remote Nozzle Permits High Production and Safety

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 405-417

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper presents a "nozzle car" which was developed for tunneling at high production rates in questionable safety conditions. Three design criteria were used: (1) ability to SC over the muck pile to maximize the curing time of the green SC, (2) potential for high production rates (up to 14 cubic yards per hour), and (3) provide safety for the crew (the boom was hit several times by falling rock, indicating that a hand-held nozzle would have been impossible to use safely in these conditions). Over a

3 month period a rate of 1 cubic yard per 7 minutes was achieved. The nozzle car was built around a cast frame muck car chassis and a Joy roll-over boom with a 4 foot extension. A 5 foot slide extension was built into the car deck but was not used, as a locomotive was coupled directly to the SC train. Proper lighting was a problem, but adjustable quartz lights were used successfully. The hydraulic pump size was adequate for allowing the nozzle operator to engage 3 different remote functions simultaneously. Nozzle maintenance costs were significant, and improvements were investigated. The targets were maintenance costs of 2 dollars per cubic yard and production rates of 12 cubic yards per hour. Other criteria were initial set in 3 minutes, final set under 10 minutes, 2000 psi CS at 24 hours, and 4000 psi CS at 28 days. The first revision of the nozzle was an enlarged water ring with a flat gasket. This improved on gasket wear, but increased leakage of water. The second revision used a larger diameter pipe and the project nozzle was economical and improved leakage. However, the improved nozzles were not meant for hand-held use for any length of time, and would not have been feasible without the nozzle car boom. Although the nozzle car provided adequate safety for the nozzle operator against rock falls, there were still cases of SC burns. The author stresses that the best safety program begins with education. Use of special garb is encouraged to prevent SC burns, including helmets with filtered air for the nozzle operator.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH05-016

AUTHOR(S): Deng, R., Chen, Z., Peng, X., and Li, Z.

PAPER TITLE: KHG Type Low-Dust Shotcrete Set

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Coal and Science Technology

DESCRIPTIVE BOOK NOTE OR EDITOR: Peking

VOLUME & NUMBER OR REPORT NUMBER: Number 1

CORPORATE AUTHOR OR PUBLISHER: -0-

MONITORING AGENCY: -0-

PUBLICATION DATE: January, 1985

PAGES (papers): pp. 20-22

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: Concrete construction, shotcreting, concrete mixers,
concrete mixing, construction equipment, dust abatement

REVIEW: Review consisted of detailed abstract written in English, with the actual reference written in Chinese. The shotcrete machine has undergone technical appraisal. The specifications for the KHG Type Low-Dust Shotcrete Set are as follows: (1) low dust content at the material feed point with the application of double suction assisted by compressed air, (2) separation coefficient reaching 95.5% with the application of a separation tank and with stirring and feeding, (3) cleaning rod and mixing valve installed in the mixing system, (4) a rotor-type effective SC machine with an average capacity of 5.3 cubic meters per hour, and (5) an average dust content of 5-15 milligram per cubic meter.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-001

AUTHOR(S): Mason, E. E.

PAPER TITLE: Keynote Address, Shotcrete for Ground Support

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 5-16

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author provides a historical perspective to coarse aggregate SC. The author first heard of SC from Helmut Kobler, who used SC on tunneling for the Montreal Subway in 1964. A 1965 Rabcewicz article in "Water Power" was the first documented case (known to the author) of using coarse aggregate shotcrete for ground support. German literature was helpful to the author. The author was involved in SC use for the Canadian National Railways. Their experience was very good, with SC providing support in some extremely poor soil conditions. Several other

cases are noted where SC was used successfully. The author notes the poor reasoning of using SC as an appendage of standard steel support. The NATM method, which uses light steel U-sections as SC reinforcement is mentioned.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-002

AUTHOR(S): Golser, J.

PAPER TITLE: The New Austrian Tunneling Method (NATM),
Theoretical Background - Practical Experiences

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 323-347

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author states that the NATM method has been misunderstood, resulting in mal designs and construction failures. Rock mechanical reasons for SC success are based on reducing stress concentrations by filling notches and also providing a continuous compound structure because of the strong adhesion of the SC to the lower quality rock face. Theoretical considerations are discussed for the "empirical dimensioning" used in the NATM method. In the NATM method, the SC role is

secondary to the steel rock anchoring, and the SC is primarily used to stabilize newly exposed rock faces and to prevent loosening of rock which could lead to rock anchor failures.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-003

AUTHOR(S): Monsees, J. E.

PAPER TITLE: Station Design for the Washington Metro System

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 348-351

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Loosening and movement along discontinuities in the rock mass are expected to be the major cause of rock load on station structures. Early installation of rockbolts was used coupled with SC application to minimize loosening. The computer program SAP-IV (Cal-Berkeley) was used for numerical modeling of structures. Assumed material properties are included. In all cases, the design moments and thrusts were within acceptable limits.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-004

AUTHOR(S): Laabmayr, F.

PAPER TITLE: Soft Ground Tunnel for the Munich Metro

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 352-372 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The author was tasked with preparing an alternative proposal for advancing a tunnel tube in difficult geological conditions. The original design ignored subsidence forces during cavity relaxation. The necessary lining resistance was achieved with a 2-shell SC lining. The outer ring of SC provides the initial cavity support and absorbs the deformations during stress rearrangement. The inside ring provides sealing against ground water, and also provides resistance to long-term creep loadings. The FEM was used to analyze the stress

distributions. Work has proceeded satisfactorily with no major problems. Minor problems include residual water and water blisters. Final subsidence from the tunneling was no greater than the subsidence caused by the lowering of ground water prior to the tunneling operation. The alternative method performed well and resulted in 30% cost reduction.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-005

AUTHOR(S): Cordel, R.

PAPER TITLE: Shotcrete for Ground Support, Past Experience of EDF

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 373-398

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Electricite de France (EDF) has employed SC for 6 years and summary conclusions are presented. Tests indicated that cores taken from boxes shot with SC are indicative of cores from the actual vertical walls, so that coring of the finished surface is not needed for lab testing. EDF reports difficulty in choosing cements, because of the high porosity of the SC (20-30% voids). (REVIEWER'S NOTE: Others have reported low permeability of SC layers.) EDF testing shows no significant strength gain for bigger aggregates, with the disadvantages of

increased wear on equipment and greater rebound losses. High dosage of accelerators will decrease the ultimate strength. Dry-mix and wet-mix processes are compared. EDF contractors tend to use the dry-mix process due to its flexibility of use and scheduling. EDF is studying the Swedish method of remote shooting to eliminate manual projection. Several case studies are highlighted which utilized SC for difficult situations, particularly splitting of the exposed rock faces (REVIEWER'S NOTE: similar to problems in expedient repair of structures). Use of SC with a tunnel boring machine (TBM) is less of an advantage as with blasted rock, with SC acting primarily as a sealer.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-006

AUTHOR(S): Fernandez-Delgado, G., Mahar, J. W., and Parker, H. W.

PAPER TITLE: Structural Behavior of Thin Shotcrete Liners
Obtained from Large Scale Tests

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 399-442 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Four principal failure modes were observed: (1) diagonal tension in the SC, (2) separation of the layer from the wall, (3) thrust-moment interaction in the separated portion of the layer, and (4) bending failure of the SC layers loaded by sharp-edged blocks. The mode was governed by the geometrical and boundary conditions of the layer, as well as the adhesive characteristics along the SC wall contact. The paper summarizes the results of a series of full-scale tests of thin SC layers acting

under idealized conditions. Layers thinner than 2 inches always failed in diagonal tension, with load capacity calculated as 5% of the CS times the length of contact times the wall thickness. Layers thicker than 2 inches, regardless of strength, always failed by separation from the fixed wall, with load capacity equal to 2 times the maximum tensile bond strength times the length of contact. The other failure modes occurred only when restraint was added. Important conclusions from this research are that behavior can be predicted if a carefully planned instrumentation plan is utilized in the field and also that the empirical rules used in design of thin SC layers provide reasonable design parameters.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-007

AUTHOR(S): Holmgren, J.

PAPER TITLE: Thin Shotcrete Layers Subjected to Punch Loads

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 443-459

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper documents tests for punching of SC performed in Sweden. Important conclusion are that: (1) SC structures often fail due to high adhesion forces at the SC-rock interface, (2) only a narrow band of SC carries the load at a joint, (3) reinforcement of a planar structure is of little use unless it is combined with rock bolts or clasps, (4) proper reinforcement leads to a strong and ductile structure, and (5) a SC arch shall always have supports, and will have high load capacity even if the arch loosens from the rock.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 100

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-008

AUTHOR(S): Nakahara, A.

PAPER TITLE: Shotcrete Application for the Seikan Tunnel

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 460-474

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Flood accidents have been a problem for undersea tunneling. SC is presently used because: (1) it quickly stabilizes ground, (2) it leaves no temporary (timber) support behind the lining, and (3) SC is easy to apply. Four problem areas occurred: (1) rebound - mix proportioning and nozzle adjustment helped with rebound, (2) hardening agent - use of water glass reduced workability and increased the hazard to workers, but did increase hardening, (3) working procedure - pipe clogging can be a problem, with dry-mix concrete having an

advantage in delivery distance, and (4) working environment - dust control is a major problem for SC, particularly for dry-mix SC. CS is a function of both the W/C ratio and also the angle of nozzle spraying.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-009

AUTHOR(S): Ward, W. H. and Hills, D. L.

PAPER TITLE: Sprayed Concrete: Tunnel Support Requirements and
the Dry Mix Process

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 475-532

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Sprayed concrete acted as a structural arch in
circumferential compression in the experimental tunnel.
The SC was subjected to high early strain rates, with
peak instantaneous compressive strain of about 0.02% at an
early age and peak values of 0.09% in the first month.
The loading attracted by the SC arch depends critically
on the amount of dilation allowed in the rock before
placement of SC, and for controlled dilation depends on
the rate of early concrete stiffening. For economy and

safety, the rate of stiffness gain of the SC should be optimized with respect to the dilation properties of the rock and the timing of construction operations. SC was found to be versatile, but more development and better control is needed. Limited data showed that dry-mix process SC is more variable, with variability reduced by using a longer nozzle and presetting the water amount. The use of an accelerator, when correctly dosed, allowed spraying at a higher water content for maximum early strength and minimum rebound, although effects on ultimate strength were not evaluated.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-010

AUTHOR(S): Treichl, H.

PAPER TITLE: Construction of the Arlberg Road Tunnel East (ATE)

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 533-555

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: SC is recommended for tunnel support, for 3 main functions: (1) as a seal against weathering, (2) as cavity lining to avoid stress concentrations, and (3) to form a structural arch. In all cases, the close bond and adhesion is of major importance. A case study is documented where SC use helped reduce construction time by about 2 years. Thorough quality control is noted as an essential part of the project. Test panels are shot, with and without accelerator, and cores and cubes are

taken from the panels. Testing included permeability and freeze-thaws tests as well as strength tests.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 103

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-011

AUTHOR(S): Franklin, J. A.

PAPER TITLE: An Observation Approach to the Selection and Control
of Rock Tunnel Linings

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 556-596 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper discusses the fundamental differences between analytical design methods and empirical design methods. Much of the discussion is on estimation of block size and shear strength. The author concludes that empirical methods will more likely provide an optimum design because of the uncertainties in the quality of the input data for analytical methods. (REVIEWER'S NOTE: This is interesting reading, but not really useful information at

this stage of Subtask 2.01. Should be read in detail when SC is pursued in greater depth.)

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-012

AUTHOR(S): Blindow, F. K. and Wagner, H.

PAPER TITLE: Contractors Experience with "The New Austrian
Tunnelling Method" (Economy and Flexibility)

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 597-612

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case study is presented where SC was used as an alternative method instead of a formwork concrete inner shell. Cost savings of up to 40% were achieved with less surface disturbance. SC is recommended for use: (1) in geometrically complex areas, (2) in areas with changing cross sections, (3) in railway stations, and (4) on short distances. The main disadvantage is the need for experienced crewperson.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-013

AUTHOR(S): Kobler, H. G., Corrales, C., and Qeseda, E.

PAPER TITLE: Shotcrete as Underground Support of Arenal Tunnel
Project

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 613-631

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The power authority for Costa Rica, ICE, has used SC for temporary underground support, with the dry-mix process as the principal method. SC was credited with the excellent advance rate of up to 75 meters per week. SC placed alone or in combination with other support components provided high quality, easily accessible, and economical tunnel support.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-014

AUTHOR(S): Crawford, J.

PAPER TITLE: Rehabilitation of Niagara Falls Tunnel

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 632-639

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case study is presented. All original bids for a wastewater tunnel at Niagara Falls, NY, were rejected and the project was rebid. The rebidding process caused the contract to be awarded in October, requiring wintertime construction. The construction was completed under difficult environmental conditions, but few details were included in the paper.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-015

AUTHOR(S): Marulanda, A. and Eslava, L. F.

PAPER TITLE: Experiences with the Use of Shotcrete in Soft Rocks

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 640-674

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Two case studies are presented of tunneling projects in soft rock. Theoretical considerations, including stress concentrations, are briefly discussed. Failures occurred which were attributed to inadequate design. The use of steel ribs is believed to have interfered with the working SC system. The conclusion was that light, closely spaced steel ribs reduce the SC system capacity, and that light steel supports spaced far enough apart to reduce stress concentrations can reinforce the SC, with SC becoming the principal means of support. However, in

overstressed ground, where yielding is not desirable, heavy steel ribs are recommended as the principal support system, with SC acting as reinforcement.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-016

AUTHOR(S): Brierley, G. S. and Cording, E. J.

PAPER TITLE: The Behavior During Construction of the Dupont
Circle Subway Station Lining

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 675-712

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The study presented herein was to evaluate the short-term performance of the tunnel lining. Difficult geologic conditions were described, with the most significant being foliation shear zones, which led to overbreak and fallouts. The construction process included a combination of rock bolting and SC, with an initial thickness of SC of 2 inches and final thicknesses ranging from 6 inches to several feet (larger thicknesses were required in overbreak areas). The tunnel lining was

instrumented with extensimeters, strain gages, and temperature probes. During initial curing, the lining temperature increased to about 60 F above ambient. Within a short time, the lining cooled and cracking attributed to temperature related tensile stresses occurred with spacing of 10 to 30 feet. The structural analysis computer program STRUDL was used to analyze the tunnel system. Conclusions included the following: (1) instrumentation worked well, with vibrating wire strain gages recommended, but strain levels were hard to interpret due to large changes in SC temperature and E, (2) rock mass movements occurred primarily along geologic discontinuities, (3) about 85% of all ground load related deflections occurred within one diameter of the top heading elevation, (4) no systematic moment pattern was observed for the lining, (5) the program STRUDL was found to be a useful analysis tool, with relations developed to predict thrust, moment, and deflection, (6) excavation of the bench below the lining caused increases in lining deflection, thrust, and moment, (7) the rockbolt array was an important factor in reducing block movements, and (8) thrust in the lining was carried primarily by the SC, although use of steel ribs was found to be beneficial.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-017

AUTHOR(S): Voort, H.

PAPER TITLE: Tunnel Instrumentation

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 713-721

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Convergence bolts are recommended as a means of monitoring overall tunnel displacements. Rod extensimeters are recommended for monitoring rock loosening. An instrumented rock bolt is recommended for monitoring of rock bolt performance. Hydraulic stress cells of the Gloetzl type were used to monitor both the contact stress and the concrete stress. Examples are given of situations where instrumentation can economically improve safety. The overall conclusion is that the use of instrumentation provides the information

needed to control the behavior of rock around the tunnel void and is important for safety and economy.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 110

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-018

AUTHOR(S): Selmer-Olsen, R.

PAPER TITLE: Examples of the Behavior of Shotcrete Linings
Underground

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 722-734

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Norway has in place about 15 miles of SC tunnels. In Norway, SC has been an alternative to cast in place concrete linings, and economics often decide when SC will be used. Early use of SC in the 1950's was for thin linings in good quality rock. Recent inspections of SC linings up to 25 years old confirmed that they had served their purpose perfectly. Localized areas of delamination were attributed to improper cleaning of rock prior to SC application and also due to parallel foliation leading to

failure behind the SC layer. Rock bolting and reinforcing nets were later adopted in foliated areas and provided improved strength. Use of the rock bolted, net reinforced SC system was used in the 1960's for permanent ground support in difficult geologic conditions. However, use of SC has not always been successful in Norway. Freeze-thaw conditions have led to delamination failures, mainly due to the trapping of seepage water behind the SC layer. It was noted, however, that this condition "often takes ... some years." Another failure problem is due to swelling of large clay gouges. Failures of SC tunnels have occurred although cast in place tunnels in similar areas have performed well. No total collapses have occurred in Norway due to the swelling process. Good performance of SC linings has been noted in supporting small clay gouges in good quality rock. Other problems have been caused by squeezing phenomena in crushed rock zones. It is concluded that SC can provide excellent support in many cases, but that geologic considerations must be accounted for before construction, because SC during construction can hide potential long-term problem areas.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-C19

AUTHOR(S): Mason, R. E.

PAPER TITLE: Shotcrete for Ground Support - Summary

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 735-742 TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Several summary conclusions were drawn and are summarized. Fiber-reinforced SC has become a viable alternative to wire mesh SC. The use of accelerating admixtures for SC has progressed, and the new organic accelerators have great potential. Variability in reported CS of SC may be attributed to variability of the product, inconsistencies in reporting procedures, and panel testing on unaccelerated SC applications (accelerators have been shown to reduce ultimate strength). Standardization of field control procedures

is needed for SC if true quality control is to be achieved. Rebound is a misunderstood quantity, and new methods of testing should be standardized. Use of remote controlled nozzle systems should be used in many cases to improve safety and production. Batching equipment has improved and improves SC quality and eliminates contractor reliance on ready-mix suppliers. Improvement in dry-mix equipment has reduced some of the advantages of the wet-mix system and has highlighted some of the wet-mix disadvantages. Little progress has been reported on the combination of SC placement with excavation by full face tunnel boring machines, although cutter boom mining machines are reported to be compatible with SC application. Lump sum payment provision have become more common since they encourage good workmanship and provide protection to the owner, but contractors still favor payment by volume delivered to reduce their risk from unforeseen conditions. Tunnel design is currently provided using theoretical and/or empirical methods. There is a need for design methods which can be altered as a result of feedback from observation or instrumentation. A large number of case histories highlight the impressive utilization of SC around the world. SC is seen to be an important international tool for tunneling in extreme conditions. A new design method called the NATM method has realized economies even though it is labor-intensive and requires experienced engineers and contractors. In general, SC has performed well for short term support. Some failures have been reported, typically attributed to freeze-thaw or ground-swelling conditions, which usually occur a few years after construction.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-020

AUTHOR(S): Kobler, H. G.

PAPER TITLE: Dry-Mix Coarse-Aggregate Shotcrete as Underground
Support

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 33-58

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Case study data is presented for use of SC in tunnels.
(REVIEWER'S NOTE: Much of the discussion is similar to a
later paper by Kobler which is reviewed in more detail.)
Both temporary and permanent support is addressed, with
mix proportions and application techniques described.
Use of admixtures is discussed. Use of calcium chloride
will provide CS of about 1500 psi in 24 hours. In
high-humidity areas, excessive hydration can cause line
clogging. Such condensation can be overcome by a small
air receiver with a drain valve in the air line. Rebound
is a problem for coarse mixes, with 1.3 to 1.7 cubic
yards of dry mix required to produce 1 cubic yard in

place. A mortar base coat is recommended for coarse aggregate mixes. Quick-setting admixtures and low W/C ratio should be used in subzero conditions. In addition, preheating of aggregate and mix water is recommended. In some cases, space heaters should be considered. Dry-mix with coarse aggregate can be delivered at rates of about 10 cubic yards per hour. QC is very important for coarse mixes. Use of traditional or jetted cylinders is not recommended. Recommended QC methods include use of 3x3 foot test panels and coring of the structure. Cored samples should be taken both parallel and perpendicular to surfaces to ensure testing of laminations. Shrinkage cracks may give the false impression of impending failure. Cost studies from almost identical tunnels showed a cost reduction of 20% for SC use.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-021

AUTHOR(S): Keifer, O., Jr.

PAPER TITLE: Multiple Layer Shotcrete Tunnel Lining

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Shotcreting

DESCRIPTIVE BOOK NOTE OR EDITOR: -0-

VOLUME & NUMBER OR REPORT NUMBER: ACI Special Publication SP-14

CORPORATE AUTHOR OR PUBLISHER: Committee 506, The American
Concrete Institute, Detroit,
Michigan

MONITORING AGENCY: -0-

PUBLICATION DATE: 1966

PAGES (papers): pp. 93-98

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A combination of rock-bolting with coverage of structural SC was used. Three 2 inch layers of SC were used, with each reinforced with welded wire fabric. No finishing procedures were used, since it was felt that screeding, rodding, troweling, or mortar flashing would probably degrade the SC. Cubes from panels and wire basket test cylinders were both used for QC testing. The mix used was 1:3.5, based on qualification tests. Membrane-forming compound was used for curing on the final layer, with other layers kept at a relative humidity of at least 85%. The completed SC has a good appearance and has performed well in its first year of service.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 114

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-022

AUTHOR(S): Bawa, K. S.

PAPER TITLE: Development of Shotcrete for Metro Construction in
Washington

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 33-49

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: Use of SC-rock bolt system was economical for permanent support in the Washington Metro system. It was noted that the use of the terms temporary support and permanent support did not apply to the SC lining, because the temporary support coat was simply the initial layer of the permanent SC system. The project used coarse aggregate dry-mix process SC. An important specification was CS of 500 psi at 8 hours and 5000 psi at 28 days,

noting that high initial strength and high ultimate strength are conflicting requirements which have to be optimized. Choice of aggregate often depends on the available equipment. Larger aggregate sizes increase rebound, and smaller sizes increase the demand for cement (which may lead to shrinkage cracking). Most of the Metro construction used 1/2 inch maximum aggregate, primarily due to availability. Gradation had some variations, and gradation specifications were ignored if the strength requirements were met. Type I cement was used instead of Type III, because it was more compatible with the accelerating admixtures. One contractor used a special cement labeled Type II-III (characteristics between Types II and III) because it was more compatible with the accelerating admixture. The choice of admixture was based on compatibility trials, with the targets of the combined cement-admixture system being: (1) initial set within 3 minutes, (2) final set within 12 minutes, and (3) CS of 600 psi within 8 hours. Setting times were determined by Gilmore needles (ASTM C 266), with W/C ratio fixed at 0.40. CS was determined as in ASTM C109. Testing of the final concrete mix was based on both laboratory and field tests with targets of: (1) CS of 500 psi at 8 hours, (2) CS of 2500 psi at 72 hours, and (3) CS of 5000 psi at 28 days. Test specimens for laboratory CS tests were 3x6 inch cylinders. In addition, 3x3x12 inch beams were used for flexural strength tests, with target of FS at least 15% of CS. Field tests used 3x3 foot panels with SC thickness of 3 inches. Test specimens were 2-3 inch cores and 3x3x12 inch beams. Use of field testing is encouraged, since it tests all phase of the production at one time, including skill of the nozzle operator. Coring was used for QC during construction. Specimens were removed in each case (8 hours, 72 hours, and 28 days) immediately before testing for CS, and were therefore tested under field-cured conditions. At least 2 specimens were taken for each 50 cubic yards of application at each age. Each core was visually examined prior to testing to determine uniformity and to check for laminations.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-023

AUTHOR(S): Jones, R. C.

PAPER TITLE: Shotcrete Practices at the Henderson Mine

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 50-57

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: A case history is presented where a SC-rock bolt system was the best available system for underground support. The mine uses about 600 cubic yards of SC per month with 2 SC placers and three underground transporter trucks. Maintenance keeps one placer out of service about 1/3 of the time. Each machine can apply 20 to 25 cubic yards each 6.5 hour shift. Batching is done from a surface plant and uses Type I cement. Dry mix is transported by truck to the shaft collar, with cost to the collar of

about \$22 per cubic yard. The dry-mix is dropped down an 8 inch slick line. A decelerator directs the material out of the shaft and into a waiting underground transportation truck. Use of a hopper was abandoned because the dry-mix material packed so tightly that it could not be readily dumped. Air carried down with the dry-mix caused dusting problems within the mine until proper venting was installed. The placer truck is charged by a conveyer belt from the transportation truck. A solution of calcium chloride equal to 2% of the cement weight is added to the mix. The SC is placed by a hydraulic boom on the front of the placer boom. Rebound is reduced because the nozzle operator has a better view of the overall spraying operation. In addition, safety is improved because large slabs of rock can fall. Another safety problem is the debonding of large slabs of SC in very wet conditions. There are a few areas where the SC has failed. However, none of these failures seem structurally serious, and all can be repaired with rock bolts and reapplication, or just reapplication. All rebound from SC operations is cleaned up and used for underground roadways. There was no QC testing, and evaluations have been based on observations.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-024

AUTHOR(S): Maples, W. A.

PAPER TITLE: Summary of Session II

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 58-64

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This paper contained summaries of 3 presentations from this session. One of the presentations, by R. E. Mason, entitled "Shotcrete in the Mexico City Drainage Tunnels," was presented without a supporting paper. A summary of this portion of the paper is included separately to eliminate confusion (REVIEWER'S NOTE: see BIBNUM SH06-027). No other new technical content was included in this paper.

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 117

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-025

AUTHOR(S): Curzio, P. Q., Barazzoni, G., Nobili, F., and Anselmi, A.

PAPER TITLE: Use of Shotcrete for Tunnelling in Difficult Grounds

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 79-95

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The paper presents several case histories of successful SC use in Italy. SC was used in 1958 in the Monastero Hydroelectric Tunnel, which was characterized by very bad geological conditions including mica schist and gneiss which were very fragmented. A system of steel mesh ribs and SC was used as permanent support. The lining has had a long period of operation and has been proven successful under continuous checking. A similar system was used as

a permanent support for road tunnels in the Genoa-Sestri Levante Highway. In addition, SC proved useful in stabilizing altered, cohesionless, loose grounds for tunnel advancement. In the Milan Subway System, surface subsidence was a major problem, and use of SC allowed very fast stabilization to minimize effects on the surface. Subsidence was held to about 10 to 12 mm under civil buildings which were 30 to 35 meters high. "...according to our experience, shotcrete is ... an extraordinarily efficient and safe means for the construction of tunnels in difficult grounds and also serving to form structurally autonomous and permanent elements of complete efficiency."

ARA BIBLIOGRAPHY/REFERENCE DATABASE, 08/07/89, 15:54, ENTRY 118

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-026

AUTHOR(S): Brekke, T. L.

PAPER TITLE: Summary of Session III

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 96-100

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: No new technical material was presented herein, with only
summaries of two presented papers.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH06-027

AUTHOR(S): Mason, R. E.

PAPER TITLE: Shotcrete in the Mexico City Drainage Tunnels

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Use of Shotcrete for Underground
Structural Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, South Berwick,
Maine, July 16-20, 1973

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-45

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1973

PAGES (papers): pp. 63-64

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: This was actually a summary by W. A. Maples, because this presentation was presented without a supporting paper. (REVIEWER'S NOTE: see BIBNUM number SH06-024). Due to subsidence in central Mexico City, a main drainage tunnel was constructed to prevent flooding from storm drainage. An estimated 250,000 cubic yards of SC will be placed. Poor ground conditions were overcome with SC or with SC-rock bolt systems. A swelling red clay caused a failure in the SC in one shaft, although it was noted

that rock bolting could have probably prevented the failure. SC was used to control various cave-ins during construction. A nozzle on a hand boom was used to improve standing time. In large cave-ins, a SC-steel rib system was used. SC was used with great success in granular rock subject to high water flow. The streams were canalized in 1 to 2 inch pipes before SC application. In severe cases, advanced drill holes were grouted before the main heading was advanced and shot.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH07-001

AUTHOR(S): Bhore, J.

PAPER TITLE: Shotcrete Payment Provisions, A Contractor's View

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 269-272

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The application is dependent on controllable factors, such as water content and air pressure, and also on less controllable factors, such as geology, overbreak, and experience of crew members. The author has dealt both with unreasonable inspectors and with unscrupulous SC foreman. The resident engineer must use the code of ethics along with the scales of fair play. Safeguards are recommended for fair payment. For application, these include: (1) insistence on experienced nozzlemen, (2) proper control of batching and mixing, (3) adequate lab

and field testing (including rebound tests), (4) adequacy of spraying equipment, and (5) establishment of reasonable CS requirements. For payment, these include: (1) payment for all SC shot through the nozzle, (2) predetermination of class of SC dependent on time and accessibility, and (3) bid prices for varying quantities, including a fixed ceiling on quantity at which price must be renegotiated. Time requirements should not be used as a punitive device, since field conditions can cause delays. Contingency funds should be included in the contract to avoid legal battles.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH07-002

AUTHOR(S): Lynch, F. L.

PAPER TITLE: Payment Provisions for Shotcrete as Seen by the
Owner

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 273-283 TOTAL PAGES (books): -0-

DISCUSSION: Discussion by Kaden, R. A., pp. 277-282

KEYWORDS: -0-

REVIEW: The paper discusses SC experience by the Washington Metropolitan Area Transit Authority (WMATA) in building the METRO transit system. Early contracts had numerous difficulties, with payment provisions which often promoted waste and cost overruns. Even quantity estimates were not handled properly. In the early contracts, the owner paid based on the total quantity shot through the nozzle, with renegotiated "extra" prices when the total quantity was not within 15% of the

original bid amount. Therefore, the owner assumed all the risk and paid all the cost, providing little incentive to the contractor to be cost conscious. Later contracts were based on cost per linear foot and resulted in several improved procedures by the contractors. One contractor has set up a school for SC personnel. As owner's representative, the author states that he has no desire to impose unreasonable risks on the contractor, and wants the contractor to make a profit on work well done.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH07-003

AUTHOR(S): Mathews, A. A.

PAPER TITLE: Payment Provisions as Seen by the Consultant

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 284-289

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The consultant is primarily interested in the cost and quality of the finished work. The author groups these interests into 5 categories: (1) economics - the consultant should minimize the total cost of the project and give the owner a reasonable estimate of the final job cost, (2) quality assurance - the consultant should maximize and assure the quality and safety of the finished project, (3) state of the art - the consultant should encourage innovation and improvements in methods, (4) equitability - the consultant should properly and

fairly compensate the contractor while insuring that he does not make "windfall" profits and should fairly share the risks for unforeseen problems, and (5) contract administration - the consultant should simplify measurement and payment, minimize disputes, encourage performance, and improve safety. Four methods of payment are discussed: (1) pay for volume through the nozzle - an early payment method, has been largely abandoned because the owner assumes all the risk and the contractor has no incentive to reduce the SC quantity, (2) pay per linear foot of tunnel - is a lump sum method which offers simplicity, but little flexibility, and is better suited to experienced SC contractors since the contractor must bear all the risk, (3) pay per area for various thicknesses - currently favored in Europe because it compensates the contractor for what the owner receives, but it makes the contractor bear virtually all the risk, and (4) cost plus fee - impractical for all but small jobs and special cases, although it was a favored method when SC was in the development stages. Caution is advised in all specifications, because there are cases where an unscrupulous contractor could be low bidder but manipulate quantities so that the pay is much higher than the second bidder. SC must be treated as a part of the total picture and alternative proposals should be given fair consideration to promote lower cost and higher quality.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH07-004

AUTHOR(S): Amos, M. J.

PAPER TITLE: Payment for Shotcrete from the Construction
Management Viewpoint

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 290-296

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: From the construction management point of view, there are 2 concerns: (1) the method of payment should encourage good construction practice, and (2) the method of payment should be capable of only one interpretation for both measurement and payment. Use of SC as a permanent tunnel support has caused measurement to be a bigger concern. Both the receiving and final surface are irregular, making measurement difficult. The most common method of payment is the volume of SC through the nozzle. This

method does not encourage good construction practice. This method has the advantage of easy measurement (unless a maximum rebound clause is added). Use of a lump sum method is judged best by the author because the risk is shared, the budget is relatively fixed, and good workmanship is encouraged.

ARA BIBLIOGRAPHY SYSTEM NUMBER: SH07-005

AUTHOR(S): Mayrhauser, W.

PAPER TITLE: The Application of Shotcrete in the NATM

DESCRIPTIVE TITLE NOTE: -0-

BOOK/REPORT TITLE: Proceedings, Shotcrete for Ground Support

DESCRIPTIVE BOOK NOTE OR EDITOR: The Engineering Foundation
Conference, Easton, Maryland,
October 4-8, 1976

VOLUME & NUMBER OR REPORT NUMBER: ACI Publication SP-54

CORPORATE AUTHOR OR PUBLISHER: The American Concrete Institute,
Detroit, Michigan and The American
Society of Civil Engineers, New
York, New York

MONITORING AGENCY: -0-

PUBLICATION DATE: 1977

PAGES (papers): pp. 297-322

TOTAL PAGES (books): -0-

DISCUSSION: -0-

KEYWORDS: -0-

REVIEW: The NATM method uses steel rings for rock support, with a SC shell for sealing. Design methods are discussed. Additional thickness for reduced strength SC is discussed. A case study is discussed where the NATM method provided a safe and cost effective solution. Highly qualified engineers and crew are essential for safety and economy when using the NATM method. The method is still being improved.