# SHOTCRETE IN CONCRETE RESTORATION

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## ABSTRACT

Spray applied mortar or concrete have become used extensively in the repair of concrete structures. This paper introduces dry and wet process shotcrete and discusses their respective advantages and disadvantages. The limitations of conventional shotcretes are reviewed and novel shotcrete materials, which include fibre reinforcement, silica fume and polymer modification are presented. This paper presents and reviews a number of projects including the restoration of parking garage, bridges, marine structures, dam and industrial concrete.

## INTRODUCTION

The double-chambered gun, developed in the early 20$^{th}$ Century by an American, Carl Akeley, brought the development of dry process shotcrete, known in North America “Gunite”. The wet process shotcrete was introduced in North America only in the early fifties after the development of equipment, which enabled the pneumatic spray application of mortars and concrete.

American Concrete Institute Publication, ACI 506R-85, "Guide to Shotcrete" defines shotcrete as "mortar or concrete pneumatically projected at high velocity onto a surface". (1) The application process falls into two groups: dry and wet mix shotcrete processes.

The dry mix process, often called "gunite," uses a dry blend of the cementitious binder mixed with aggregates. The blend is prepared by batch mixing at the site or by transit mixer. Often it is prepared in a dry blender and delivered to site pre-bagged. Dry material is pre-wetted by adding water to get approximately 3% moisture content to reduce the dusting during the application. The cement aggregate blend is fed into the delivery hose by feeding equipment. This could be metering devices such as a feed-wheel, rotor or feed-bowl. The material is then carried by compressed air into the nozzle. Water is added at the nozzle, mixed with the dry material and delivered at high speed to a substrate.

The wet mix shotcrete process uses the wet mortar or concrete mix prepared using standard concrete/mortar mixing equipment, or the mix is prepared in the mixing chamber of the delivery equipment. The wet mix is metered into the delivery hose by a concrete pump or is moved by compressed air from the pressurized vessel of the delivery equipment. Additional air is introduced at the nozzle, and the material is delivered at high speed to a substrate.

Both dry and wet processes will produce mortar and concrete of satisfactory performance, but each present unique advantages and disadvantages. Table 1 compares the main features of the dry and wet processes in the application of conventional cement aggregate mixes. The capital and maintenance costs of the equipment, suitability of the particular process to the given application, placement characteristics and physical properties of the plastic and hardened shotcrete material will also affect the choice of the process used in a given application.

When compared with conventional concrete, the dry shotcrete mix design will use a higher cement amount to compensate for the loss of aggregate due to rebound. Water reducing and air entraining admixtures are not used with the dry process.

The proportioning of the wet shotcrete can be done according to ACI 211.1 with the aggregate content correction for pumped concrete. Water reducing admixtures are often incorporated in the mixes to lower water content and air entraining agents may be used, especially when the placed shotcrete will be exposed to freeze/thaw cycles. For overhead and vertical applications, set accelerators are used in both the dry and wet shotcrete. Strength development accelerators might be used when a high early strength is required. For more detailed treatment of shotcrete mix designs, refer to "Guide to Shotcrete" ACI Committee 506 in Reference 1. Typical aggregate distributions used in both dry and wet process shotcrete, specified by the ACI Committee 506 are shown in Table 2.

The properties of properly designed and applied shotcrete are very similar to conventionally placed concrete. The quality of the dry shotcrete is largely controlled by the nozzleman, and incorrect application may result in poor compaction and formation of “sand pockets” that may decrease the durability of the shotcrete application. The conventional wet shotcrete uses a higher water cement ratio when compared with the dry process. This also may decrease the strength and durability, but the wet process allows good control of the water cement ratio and incorporation of the air entraining agents, which will provide very good freeze/thaw and salt scaling resistance. Reinforcing bars, wire fabric (uncoated or galvanized) are used as reinforcement as in conventional concrete.

Shotcrete has traditionally been used in mining and tunnelling, rock stabilization, irrigation canal construction and water storage tank construction, to name the most important uses. More recently shotcrete has been used in concrete restoration.

The shotcrete process is suitable in a number of concrete restoration situations such as:

- Where formwork is not practical
- Where formwork can be reduced or eliminated
- Where normal casting into formwork can’t be employed
- Where a thin and/or variable thickness layer is required
- Where access to the work area is difficult

The limitations presented by conventional (aggregate cement) shotcrete, placement technique and the physical properties of the resulting material have restricted their use in concrete restoration. Recent developments in concrete material technology have resulted in the introduction of novel shotcrete materials in an attempt to improve the properties and placement efficiency of conventional shotcrete.

## NOVEL SHOTCRETE MATERIALS

### Polymer Modification

The first modification of shotcrete materials, dry or wet, has been in the use of polymer modifiers, acrylic and butadiene styrene latexes. The introduction of latex into the mortar or concrete mixes increases the tensile and flexural strength, decreases the permeability and improves the chemical resistance. The polymer modification usually reduces drying shrinkage cracking and allows for a simple air dry curing. However, addition of latex also presents problems. Not only is the cost of the material considerably increased, but also, particularly in the wet shotcrete mixes, high air content may result from the addition of the polymer modifier. When layering, the polymer sealed surface may cause interlayer bonding problems, particularly in wet environment and freeze/thaw conditions; e.g., in the Canadian marine environment. More recently, dry polymer modifiers have been introduced instead of liquid dispersion based latexes. The use of dry polymer is particularly suitable in dry shotcrete blends where it eliminates the use of two components material systems.

### Pozzolanic Admixtures

The most significant recent development has been the use of the silica fume admixtures in shotcrete materials. Silica fume is an amorphous silicone dioxide, a by-product of the ferrosilicon industry. The very fine particle of silica fume, approximately one hundred times smaller than that of the cement particle, reacts by a pozzolanic reaction with the lime (Calcium Hydroxide) generated by cement hydration. This results in increased compressive strength, considerable decrease in permeability and improved chemical resistance. The addition of silica fume in dry or wet shotcrete materials increases the internal cohesion of the mixes and thus allows a high vertical or overhead build-up. The addition of silica fume also decreases the rebound of the material during the application. This is particularly noticeable in wet shotcrete materials where the rebound can be reduced to very small amounts. The internal cohesion of the shotcrete mixes containing silica fume also allows early exposure of the shotcrete mortar or concrete to water; e.g., tidal water in marine applications. Silica fume is considerably less expensive than polymer modifiers. One of the negative aspects in use of the silica fume is susceptibility of the mixes to plastic shrinkage cracking, but this s can be well controlled by a proper curing procedure, mainly in the early curing. The high surface area of the silica fume also requires the use of high range water reducing agents in wet shotcrete.

**Fibre Reinforcement**

Fibre reinforced mortars and concrete were introduced in the concrete technology approximately twenty years ago. There are three main types of fibres that have been used: steel fibre, alkaline resistant glass fibre and polymeric fibres. In larger quantities the fibre reinforcement can replace the traditional reinforcing bars or steel mesh reinforcement. In smaller quantities the main function of the fibre is in the reduction or elimination of drying shrinkage crackingThe introduction of fibres increases the tensile and flexural strengths and crack resistance. The reinforcing effect of the fibres increases with the amount and the modulus of elasticity of the fibre used. The steel fibre provides a very effective reinforcement and has been the most widely used in shotcrete mixes to date in both dry and wet shotcrete. It is often mixed with all dry materials first and bagged large "bulk" or smaller paper bags for delivery to the site. The steel fibre can also be mixed on site with sand and cement using dry blending/batching equipment. Steel fibre reinforced shotcrete has been used in tunnel construction and repairs and marine concrete restoration. The applications are characterized by the larger volume of material used and the greater thickness of the applied layer. Steel fibre shotcrete is difficult to use in thin section applications below approximately 60 mm.

Alkaline resistant glass fibre exhibits a high modulus of elasticity and can be easily mixed into mortars in larger quantities than the steel fibre. Also the finishability of glass fibre reinforced mortar is very good. Alkaline resistant glass fibre is typically used in the wet shotcrete process, but it could be incorporated in the dry process as well. Alkaline resistant glass fibre reinforced shotcrete is used primarily in concrete restoration: ceilings, walls and beams of concrete parking garage structures, bridge structures and in industrial concrete restoration. The application is characterized by the use of the material in thickness varying from "feather edge" to 5-10 cm in thickness. Polymeric fibres, typically mono-filament polypropylene, have been also used in the dry or wet shotcrete processes. The fibrillated polypropylene is primarily used in the wet shotcrete process. The main limitation of the polypropylene fibre reinforcement is its low modulus of elasticity. The polypropylene is primarily used to control plastic shrinkage cracking and to a limited degree, drying shrinkage cracking. Its main advantages are relatively low cost and chemical inertness in alkaline mortars and concrete.

Recently, non-corrosive glass fibre reinforced plastic grid reinforcement has been developed for shotcrete and its main application has been in new tunnel construction and tunnel repair.

Typical mix designs for dry and wet process shotcretes and their properties in the plastic and hardened stages are given in Tables 3, 4 and 5 respectively (Morgan, 1997).

**Low Velocity Shotcrete**

The ACI document referred to above defines shotcrete as material projected at high velocity. More recently a new type of shotcrete method has been developed using a low velocity delivery. In this technique a low air pressure and volume is used just to deliver the material to the nozzle of the shotcrete equipment. The shotcrete "flows" out of the nozzle in a similar way to the action of a caulking gun. This technique is used in overhead or vertical repairs of concrete. It is particularly suitable for relatively small volume repairs as a replacement for hand trowelling. A thin layer of wet shotcrete is first applied at a higher pressure to provide a "prime coat", the air pressure and the volume is then reduced to allow the "caulking" like action and filling of the delaminated concrete. The actual air pressure and volume depends on the specific equipment and the shotcrete mixes must be specially formulated to allow this technique to function properly.

## CASE HISTORIES – WET SHOTCRETE PROCESS

**Parking Garage – Chicago, Illinois, USA**

Situated in downtown Chicago, the 2,200 car capacity North Grant Park Garage is a 60 year old underground parking structure, serving approximately 3, 500 patrons a day. The roof of the garage supports the Grant Park landscape and Michigan Avenue. The parking structure consists of two main levels and a mezzanine parking level. In plan its dimensions are approximately 366 m by 107 m. Its construction consists of cast-in-place reinforced concrete flat slab supported by 610 mm. diameter columns spaced 8.85 m. on center. Roof slabs are 305 mm thick, while intermediate level slabs are 254 mm thick. The foundation slab is 380 mm thick at bay centers and 686 mm at the base of columns. The columns have 1.68 m diameter conical capital topped by 3 m. by 3 m. by 127 mm. drop panels. For a number of years, the garage has been experiencing an accelerated rate of deterioration, leading to extensive delaminations and spalling of the concrete floor slab and ceiling. Based on various inspections and petrographic tests, the deterioration was primarily attributed to chloride-induced corrosion of the embedded reinforcing steel in the concrete slab. In the past, several attempts were made at repairing small patches in the garage ceiling by using a dry shotcrete process - gunite. While most of the applied shotcrete has served its intended purpose, failure of several other patches leading to delaminations, scaling and spalling of shotcrete has also been observed. Failure of these patches can chiefly be attributed to shrinkage cracking. Water entered the shotcrete through shrinkage cracks and caused scaling and spalling due to repeated freeze – thaw cycles. In order to achieve better quality control and to avoid defects like excessive voids, dry patches, sand lenses, excessive dusting and rebound, dry mix shotcrete process was ruled out.

Properties of an ideal shotcrete mix for this repair was outlined as follows:

- Good bond to substrate
- High compressive and flexural strength
- Minimum shrinkage
- Low permeability
- Low rebound and dusting
- High early strength
- Minimum curing
- Lowest possible overall cost

Wet mix shotcrete process, Spray-Con WS Pus, was selected to take advantage of advances in materials technology and pumping equipment. The presence of silica fume in Spray-Con WS Plus decreases the permeability and increases the strength of the repair material. In addition, increase in cohesiveness of the wet shotcrete material decreases the rebound of the applied material to a very small amount (4-5 % in this project), when compared with a conventional dry or wet shotcrete. The fibre reinforcement limits drying shrinkage cracking of the repair layer with varying thickness from feather- edge to 15 cm. The presence of the polymer modifier (latex) allows air dry curing of the applied material. Addition of a small amount of the set accelerator, Adi-Con SP 100, at the nozzle during the application allows a continuous overhead build up of layers while minimizing rebound. The mechanical properties of Spray-Con WS Plus are given in Table 6. The project was gradually undertaken from 1988 to 1993. The surface preparation consisted of removal of delaminated concrete and sandblasting of the surface. The severely corroded steel bars were replaced and a Portland cement based rustproofing material, Fibre-Prime, was applied to the existing exposed steel. The typical compressive strength results of the core samples are plotted against their densities in Table 7. Note the "strong" relationship between the density of the samples and their strength indicating the importance of good compaction of the applied shotcrete. A sodium silicate based accelerator, Adi-Con SA 100, was used in quantity of approximately 4% by weight of cementitious material, to allow a fast set and an easy, thick overhead build up. A number of tests have been carried out to determine the effect of the accelerator on the entrained air and permeability. Typical results, given in Tables 8 and 9, show no effect by the acceleration on those properties. This is attributed to the presence of silica fume and polymer, since in conventional shotcrete this type of accelerator may cause serious permeability and durability problems. The surface of the repair was protected by the polymer cement based coating Cem-Kote ST. The drying shrinkage cracking observed was minimal and the performance of the repairs has been excellent.

**Bridge Structure, Chicago, Illinois, USA**

The bridge structure exhibited severe delaminations due to a combination of alkaline aggregate reactivity cracking, freeze/thaw damage and corrosion of the reinforcing steel. After removal of the deteriorated concrete and repair and rust proofing of the reinforcing steel with Fibre-Prime, a wet process shotcrete, Spray-Con WS Plus – two component, was applied in thickness varying from 6 mm to 100 mm to restore the structure. The repair was carried out in 1991 and the performance of the repairs has been very good, with minimal drying shrinkage cracking.

**Elevated Ramp - Bridge Structure, Gdansk, Poland**
The structural repair of an elevated highway ramp in the City of Gdansk was carried out in 1995. One of the problems of this girder box structure was corrosion of the reinforcing cables. Due to uncertainty regarding the level of deterioration of the cables, the designer decided to use a high level of external post-tensioning within the girder box. For safety reasons, the buckling resistance of the girder box was increased by the application of 150 mm of Spray-Con WS ST, a wet process shotcrete, to the exterior of the girder box sidewalls. The shotcrete layer was reinforced with a heavy steel mesh mechanically fastened to the wall. A highly flexible acrylic coating, Tuff-Flex was applied to prevent any water penetration through possible drying shrinkage cracks and at construction joints, thereby protecting the entire structure. Yearly inspections show crack and delamination free performance of the repairs.

**Penitentiary- Kingston, Ontario, Canada**
The maximum-security penitentiary in Kingston, Ontariobuilt in 1835 is surrounded by a stonewall. At the beginning of the twentieth century, a thick layer of cement plaster was applied to the interior of the wall. Long-term penetration of water between the cement and the stone and consequent freezing and thawing resulted in cracking and serious deterioration of the cement plaster layer as well as the stonewall mortar joints and, to some extent, the stone. The repair design engineer decided to reinforce and protect the wall on the interior by applying an approximately 15 cm thick layer of wet process Spray-Con WS ST shotcrete. Deep cavities in the wall were first filled by conventional sand cement mix applied using a dry process shotcrete for economical reasons. Spray-Co WS ST provided the final layer. The applied layer was covered with a polymer modified cement coating, Cem-Kote ST mainly for aesthetic reason to achieve the color uniformity and to seal the minimal drying shrinkage cracking that occurred. The project was carried out in 1997 and the application has been, for the most part free of drying shrinkage cracking or delaminations.

**Waste Water Treatment Facility – Bedford, Nova Scotia, Canada**
In 1993 the concrete roof of a digester tank in Bedford Nova Scotia collapsed. The most probable reason for the failure was deterioration of its pre-stressed gunite concrete combined with a temporary excessive pressure in the tank. The concrete roof was replaced with a “gas holding” steel roof. Over the years and also due to excessive pressure, the reinforced concrete tank, which measures 10.67 m in diameter and 6.70 m high, had developed vertical and horizontal cracks. The repair required long term sealing of the cracks in the reinforced concrete wall as well as concrete protection. The designer selected two materials for the repair: alkaline resistant glass and polymer fibre reinforced, micro-silica enhanced mortar, Gem-Crete HDO, as the primary waterproofing layer and a highly flexible, polymer modified cement, Cem-Kote Flex ST as the secondary waterproofing and protective layer. After cleaning the tank by sandblasting, the vertical and horizontal cracks were covered using a galvanized welded fabric, 1.52 mm diameter 300 mm wide strip with opening 50 mm by 25 mm, mechanically fastened to the concrete. After placement of the welded wire, reinforcing fabric strips over the cracks, a 12 mm thick layer of, Gem-Crete HDO, was applied to the concrete surface of the tank. The material was mechanically applied using the “wet process” shotcrete method. The following day the surface of the primary layer was thoroughly cleaned with high-pressure water. An approximately 3 mm thick layer of flexible cement, Cem-Kote Flex ST, was rolled on in two coats. The waterproofing protective system was air cured for approximately one week before the tank was put back into use. No additional fabric reinforcement was used in the flexible cement layer. The performance of the repair has been excellent. The interior of the tank was inspected in 1997, 4 years after the installation, and no leaks or deterioration of the waterproofing system was found. Further exterior inspections in 1999 and 2002 also revealed no leaking.

**Potable Water Storage Tanks- Port Williams, Nova Scotia and Dalhousie, New Brunswick, Canada**
The pre-stressed gunite construction tanks developed severe delaminations due to leaks and freeze thaw damage and cracking. In 1987, wet process shotcrete applied Gem-Crete HDO mortar, reinforced with a high volume fraction (1.7% by volume) of alkaline resistant glass fibre and enhanced with silica fume, was used to seal and waterproof the interior of the concrete water storage tanks. The applied thickness of the layer was approximately 12-18 mm with the surface being trowel finished. The high fibre content allowed bridging of the existing substrate cracks and provided, to some degree, a structural waterproofing. The high freeze thaw resistance and high tensile strength of the repair material in this application is essential in assuring the long-term performance of the repairs. The fibre reinforcement and resulting thin section application provided very fast application and short "down time". The Port Williams tank is still in service with

no leaks and the Dalhousie tank had been leak free until its replacement in 1998.

**Dneprogess Dam - Zaporozhie, Ukraine**

The Dneprogess Dam, built on the Dnepr River in the early thirties, was for some time the largest dam in the world. The penstock wall had seriously deteriorated through a combination of poor construction method, a very low quality materials and freeze thaw damage. The deteriorated concrete was removed and all the active leaks were sealed using hydraulic "plugs" and all the cracks were waterproofed by injection of cement grout. Spray-Con WS ST has been applied to the surface in thickness varying from 5 to 10 cm. The project was carried out in 2002 and exhibits almost no drying shrinkage cracking.

**Coke Chemical Plants - Zaporozhie, Ukraine**

The reinforced concrete structures of the Coke Chemical plants were severely deteriorated by acidic attacks from coke fumes and corrosion of the reinforcing steel. Deteriorated concrete was removed by mechanical chipping and cleaned by wet sandblasting. Where possible concrete was removed around the reinforcing steel and the steel was protected by a polymer-cement based rust-proofing coating, Fibre-Prime, containing migrating corrosion inhibitors. Glass fibre reinforced, silica fume modified wet process shotcrete, Spray-Con WS ST, was applied in thickness varying from 50 mm to 150 mm. The entire surface was coated with polymer-modified cement coating Cem-Kote ST, to further increase the chemical resistance and provide more uniform colour appearance. Virtually no drying shrinkage cracking or de-bonding has been observed in the repairs. The project was carried out in 2001 and 2002.

**CASE HISTORIES – DRY SHOTCRE PROCESS**

**Marine Structures, Corner Brook, Newfoundland, Canada**

The marine structures (wharfes) of reinforced concrete piles and two-way reinforced concrete deck were constructed during the Second World War. The structures were severely deteriorated by moving ice, freeze/thaw damage and, to some degree, by corrosion of the reinforcing steel. The deteriorated concrete was removed mechanically by pneumatic chipping hammers and sandblasting and a reinforcing mesh was then mechanically anchored to the substrate. Dry shotcrete Spray-Con DS ST was selected for this restoration project, since the repair material had to be transported long distances from the wharf deck underneath the large structure. The dry process shotcrete material contained silica fume and glass fibre reinforcement. No accelerators were used. The thickness of the shotcrete layer varied between 70 to 150 mm. In order to increase the freeze/thaw resistance of the repair the entire concrete structure was coated with a waterproofing layer of polymer modified cement coating Cem-Kote ST. The typical compressive strength data are summarized in Tables 10 and 11. The test panels were "shot" vertically as well as horizontally. Table 12 summarises compares the results of the testing. The repairs were carried out in 1995 and yearly inspections show very little drying shrinkage cracking, no delaminations and there is no freeze/thaw or ice movement damage to the structure.

**Berths of Port of Saint John - New Brunswick, Canada**

The Port of Saint John dates from 1920. The marine structures in the port are subjected to the world's largest tidal range as well as a very high number of freeze thaw cycles estimated at 200-300 cycles per year. (Gilbride, 2002). In addition, there is susceptibility to alkaline aggregate reactivity cracking and deterioration due to salt-water reactivity with the concrete. The height of the concrete berths is approximately 10 meters and the tidal height is 8.5 meters. The main deterioration occurs in the middle of the tidal range, at approximately the 2-3 m high zone. The economic cost of casting the concrete into forms, shotcreting and total replacement were considered in the repair feasibility study.

Repair costs using forming and shotcrete were approximately the same - 120 to 130 $\$Cdn/m^2$ - at the time of evaluation in 1986. Repair costs were approximately 2% of the replacement costs. The shotcrete process as opposed to concrete forming was selected for the following reasons (Gilbride, 2002):

- Versatility – independent of form sizes
- Mobility – less time required to occupy the berth
- Better suited for small crew - no cranes and handling of forms
- Low cost of set up

- Availability of new developments in shotcrete material and quality control procedures

The following performance requirements were identified in selecting the shotcrete process:

- Shotcrete must be applied between strong tidal currents without being washed out
- Shotcrete should be capable of application in layer thickness of up to 120 mm in a single pass
- The use of accelerators was viewed as undesirable because of long term durability considerations
- Shotcrete should be resistant to freezing and thawing and alkali aggregate reactivity
- The selected reinforcing should have a potential for long term corrosion resistance

After reviewing the above considerations, wet process shotcrete reinforced with steel fibres and silica fume modified was selected for the repairs.

The deteriorated concrete of the wharf face was removed to a depth of 100 to 150 mm using pneumatic hammers in the 14-18 kg size range. A reinforcing grid consisting of 11 mm diameter bars placed approximately 1500 mm on centre was fastened by 16 mm threaded bars anchored into the substrate concrete at $15^o$ angle and a depth of 1120 mm. The cross-section of the reinforcement was further covered with 100mm by 100 mm by 9 mm thick steel plates. The reinforcement was placed to allow a minimum 50 mm shotcrete cover of the outer bar. Wet shotcrete was applied from a barge in two lifts, in sections approximately 9 meters high and 27 meters long. The first layer, approximately 50 mm thick, acted as an anchoring layer applied approximately to the depth of the reinforcing bars. The second 50 mm thick layer was then applied with an additional 25 mm layer placed over the reinforcement. An accelerator was used in the first lift but only in the areas where water was seeping from behind through the berth concrete wall. The applied shotcrete was wet cured for 3 days by means of water hoses placed along the work, to prevent the shotcrete from drying between the tide cycles. The shotcrete was applied during the dropping tide, to avoid damage of fresh shotcrete by the movement of the barge. The shotcrete mix design is given in Table 13 and the typical strength data are summarized in Table 14. The repairs were carried out every year from 1986 to 1995 ( except in 1988 and 1992) and a total of 200 linear meters of the berths was repaired. A condition survey showed that after 10 years of performance there was no freeze/thaw damage. Minor deficiencies included delaminations in the "feather edge areas" and some drying shrinkage cracking. Based on this ten-year performance in 1996, the repairs demonstrated that, with minor maintenance work, "the repaired berth faces should provide many more decades of effective performance" (Gilbride, 2002).

**Water Tunnel- Detroit, Michaigan, USA**

The main reinforced concrete tunnel, approximately 3 meters in diameter, bringing water into the City of Detroit, was found to require major structural restoration. Steel ribs were used to provide the primary structural support. Dry-process shotcrete Spray-Con DS ST, reinforced with stainless steel fibres, approximately 60 kg per cubic meter, was used to provide the liner and protection of the reinforcing ribs. The key reason for selecting dry process shotcrete in this project was the necessity of transporting the repair material long distances between the tunnel access manholes. Shotcrete was applied in two lifts. First, approximately 150 mm thick layer was applied to the outer level of the reinforcing steel ribs. An additional 50 mm of shotcrete was applied to provide corrosion protection of the reinforcing steel ribs.

**Note:** Some of the project descriptions include considerable technical detail. Others are mentioned without details for the sake of brevity to provide only the background information for the "Power Point" presentation of this paper. Please contact the writer for additional details if required.

**SUMMARY**

The novel shotcrete materials include fibre reinforcement, polymer and silica fume modification in addition to the cement/aggregate mix used in conventional shotcrete. Shotcrete application of these materials results in superior freeze thaw resistance and reduction of the drying shrinkage cracking exhibited by conventional dry or wet process shotcrete. A large variety application of these novel wet and dry process shotcrete materials can be found in concrete restoration, where they provide superior performance over conventional shotcrete.

## REFERENCES


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**Table 1. Dry and wet process shotcrete - comparison**

| Dry Process (Gunite) | Wet Process |
|---|---|

| | |
|---|---|
| • Variable w/c ratio<br>• Lower w/c ratio<br>• Presence of "sand" pockets<br>• Distance delivery easy<br>• Air entrainment difficult<br>• High rebound<br>• On and Off Easy<br>• Nozzle – man training difficult | • Controlled w/c ratio<br>• Higher w/c ratio<br>• No "sand pockets"<br>• Distance delivery difficult<br>• Air entrainment possible<br>• Low rebound<br>• On and Off Difficult<br>• Nozzle – man training easier |

**Table 2. ACI 506 R – 90 Gradation Limits for Aggregates for Shotcrete**

| Sieve Size, US Standard Square Mesh | Percent by Weight Passing Individual Sieves | | |
|---|---|---|---|
| | Gradation #1 | Gradation #2 | Gradation #3 |
| 19 mm (3/4 in) | 100 | 100 | 100 |
| 12 mm (1/2 in) | 100 | 100 | 80-95 |
| 10 mm (3/8 in) | 100 | 90-100 | 70-90 |
| 4.75 mm (No.4) | 95-100 | 70-85 | 50-70 |
| 2.4 mm (No.8) | 80-100 | 50-70 | 35-55 |
| 1.2 mm (No.16) | 50-85 | 35-55 | 20-40 |
| 600 mm (No. 30) | 25-60 | 20-35 | 10-30 |
| 300 mm (No. 50) | 10-30 | 8-20 | 5-17 |
| 150 mm (No. 100) | 2-10 | 2-10 | 2-10 |

**Table 3. Typical shotcrete mix designs for the repair work, at the nozzle (Morgan, 1997)**

| Material | Mix Designs (kg/m$^3$) | | | |
|---|---|---|---|---|
| | Wet Process | | Dry Process | |
| | Plain | CSF | Plain | CSF |
| Portland Cement, Type 10 | 400 | 350 | 425 | 375 |
| Adi - Con CSF | - | 47 | - | 50 |
| Concrete Sand | 1260 | 1215 | 1215 | 1205 |
| 10 mm aggregate | 460 | 485 | 495 | 490 |
| Water | 170 | 177 | 165 | 165 |
| Adi – Con SP 100 | - | Yes | - | - |
| Adi – Con AE 100 | Yes | Yes | - | - |
| **Total** | 2290 | 2274 | 2300 | 2285 |

**Table 4. Properties of plastic wet and dry process shotcretes (Morgan 1997)**

| Property | Shotcrete | | | |
|---|---|---|---|---|
| | Wet process | | Dry process | |
| | Plain | CSF | Plain | CSF |
| Slump, mm | 50 | 50 | - | - |
| Air content, %<br>before shooting<br>after shooting | <br>8.5<br>4.8 | <br>6.4<br>3.9 | <br>-<br>- | <br>-<br>- |
| Thickness to Sloughing, mm<br>Overhead<br>Vertical | <br>80<br>300 | <br>130<br>330 | <br>65<br>200 | <br>380<br>460 |
| Overhead Rebound, %<br>Vertical Rebound, % | 15<br>4 | 13<br>3 | 46<br>42 | 20<br>20 |

**Table 5. Properties of plastic wet and dry process shotcretes (Morgan, 1997)**

| Property | ASTM test | Shotcrete | | | |
|---|---|---|---|---|---|
| | | Wet Process | | Dry Process | |
| | | Plain | CSF | Plain | CSF |
| Compressive strength, MPa at 24 hrs<br>at 7 days<br>28 days | C 39 | 15<br>28<br>44 | 22<br>45<br>63 | 30<br>44<br>54 | 34<br>49<br>60 |
| Flexural Strength, MPa<br>At 7 days<br>28 days | C 78 | 3.8<br>5.3 | 4.9<br>6.7 | -<br>7.4 | -<br>8.4 |
| Boiled Absorption, 28 days | C 642 | 6.6 | 5.9 | 4.9 | 2.7 |
| Air Content, %<br>Specific Surface, $mm^{-1}$<br>Spacing factor, mm | C 457 | 5.0<br>23<br>0.25 | 3.3<br>18<br>0.36 | 4.3<br>16<br>0.35 | 3.9<br>21<br>0.26 |
| Dry. Shrink. %, 64 days | C 341 | 0.105 | 0.088 | 0.072 | 0.061 |

**Table 6. Properties of Spray-Con WS Plus (two component) fibre reinforced, silica fume and polymer modified Shotcrete – Chicago parking garage**

| | |
|---|---|
| Compressive Strength, ASTM C109 Modified | 39.5 to 48.3 MPa |
| Modulus of Rupture ASTM C27-40 | 6.2 to 7.6 MPa |
| Bond Strength with Concrete, direct tension pull-off test | Exceeds the tensile strength of concrete substrate |
| Freeze/Thaw Resistance, ASTM C666, Procedure A | Weight loss below 1% |
| Salt Scaling Resistance, ASTM C672 | Excellent |

**Table 7. Chicago parking garage – Compressive Strength-Density Data**

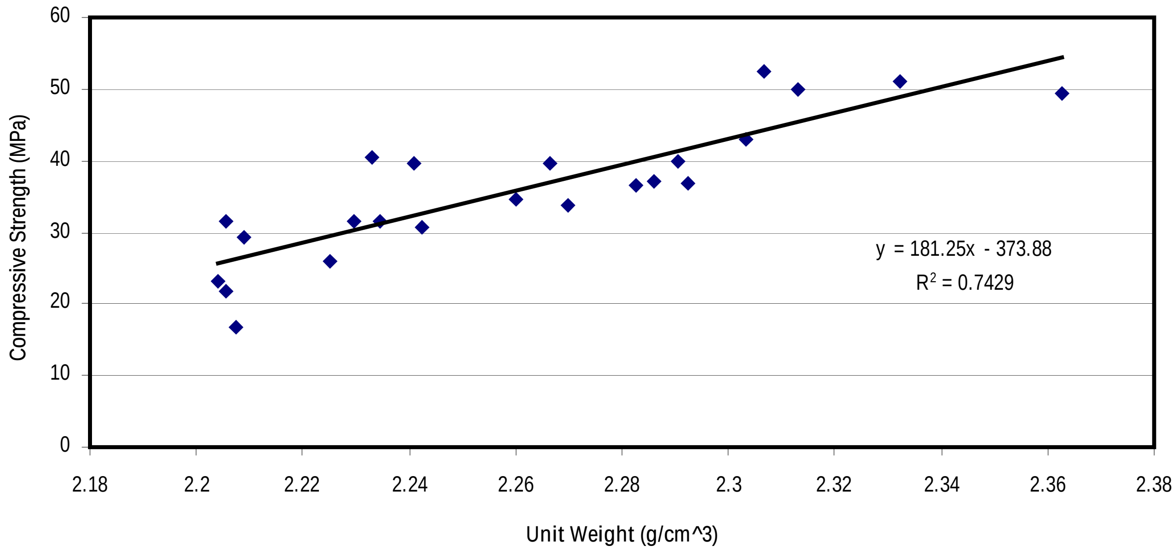


**Table 8. Chicago parking garage project – air void structures of accelerated and non-accelerated (control) wet shotcrete, Spray-Con WS Plus (two component)**

| Sample | Air Void Structure | | |
|---|---|---|---|
| | Air Content, % | Specific Surface, $m^3/mm^2$ | Spacing Factor, mm |
| Accelerated | 4.6 | 31.9 | 0.9 |
| Control | 2.6 | 33.6 | 0.20 |

**Table 9. Chicago parking garage project -chloride permeability rating of accelerated and control (non accelerated) wet shotcrete, Spray-Con WS Plus (two component)**

| Sample | Chloride Permeability | |
|---|---|---|
| | Charge Passed (coulombs) | Permeability rating |
| Accelerated | **308** | **Very low** |
| Control | **500** | **Very low** |

**Table 10: Compressive strength test data for vertically applied Spray-Con DS ST - dry process shotcrete
Corner Brook, Newfoundland**

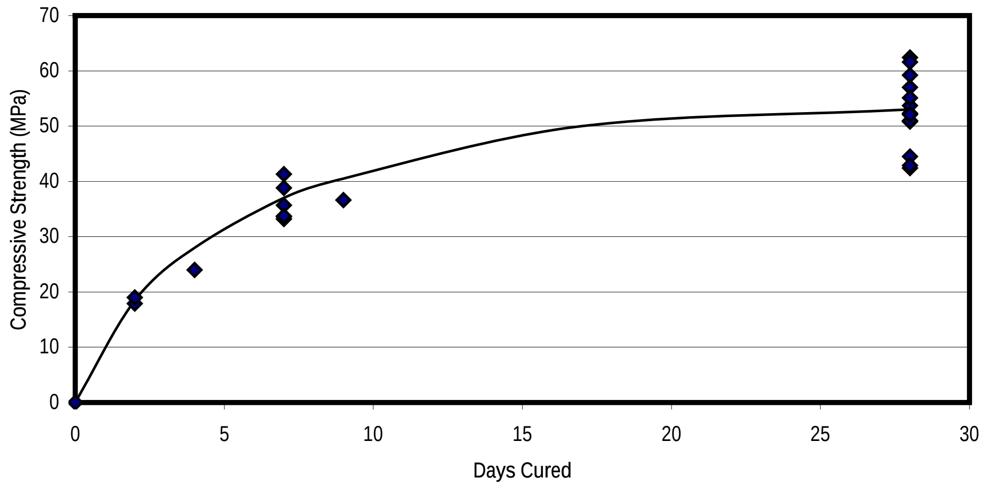


**Table 11: Compressive strength test data for horizontally applied dry process shotcrete
Corner Brook, Newfoundland**

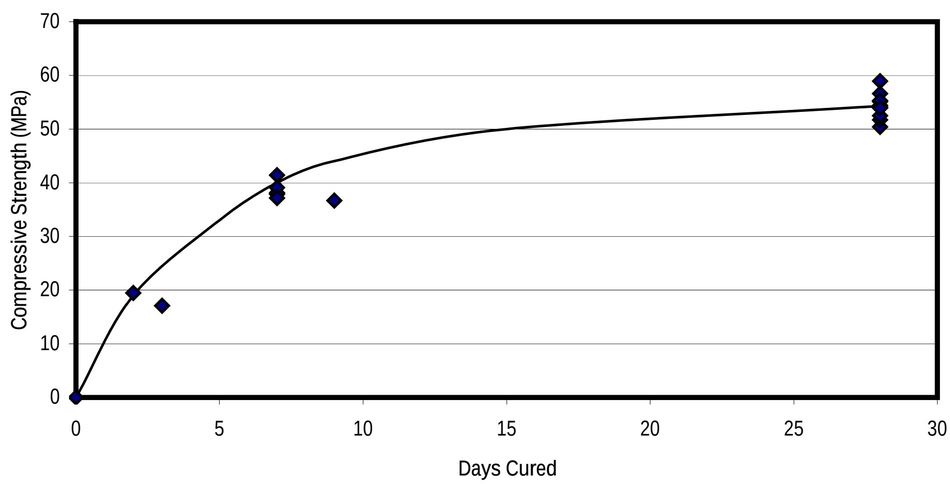

**Table 12: Comparison of compressive strength test data for horizontally and vertically applied dry process shotcrete, Spray-Con DS ST Corner Brook, Newfoundland**

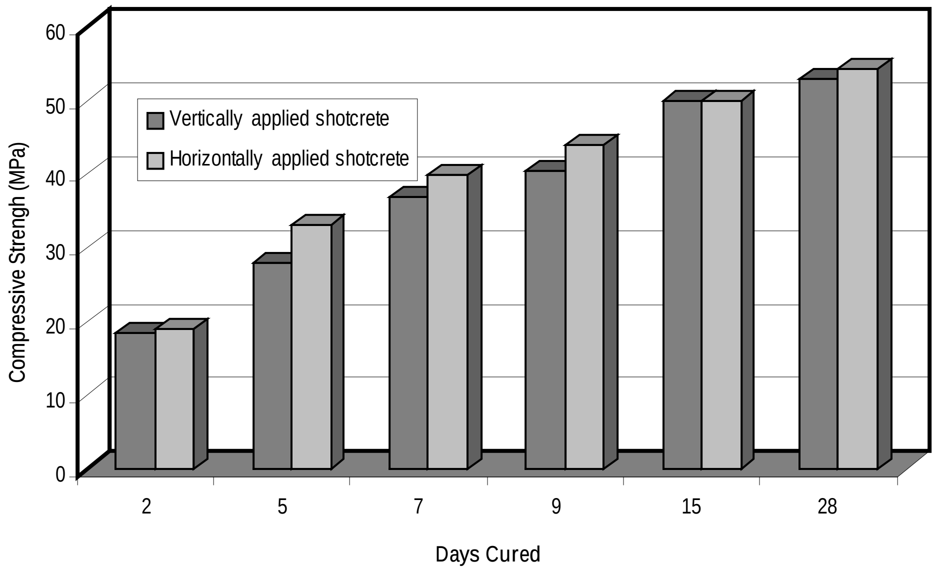


**Table13. Mix design of steel fibre reinforced, silica fume modified, wet process shotcrete, Port of Saint John, New Brunswick, Canada, Gilbride, P, et all, 2002**

| Material | Material Proportions kg/m³ |
|---|---|
| Normal Portland cement ( Type 10 ) | 400 |
| Adi-Con CSF (Silica fume) | 56 |
| 10 mm course aggregate ( SSD ) | 460 |
| Concrete sand ( SSD ) | 1100 |
| Water | 180 |
| Water – reducing admixture | 2 L |
| Superplasticizer | 7 L |
| 30 mm steel fiber | 60 |
| Air – entraining admixture | As required for |
| Air content (in place) | 7 ± 1% |
| Totals | 2265 |
| Slump | 80 ± 20 mm |
| Minimum 28 – day compressive strength | 40 MPa |

**Table 14. Copressive and flexural strengths data for steel fibre reinforced, silica fume modified, wet process shotcrete, Port of Saint John, New Brunswick, Canada, Gilbride, P, et all, 2002**

| Date Shot | Fiber Type | Fiber Dosage (kg/m3) | Compressive Strength, MPa | | | Flexural Strength, MPa | |
|---|---|---|---|---|---|---|---|
| | | | 7 days | 28 days | 56 days | 7 days | 28 days |
| 87-06-24 | D | 60 | 40.4 | 49.0 | 62.7 | 8.4 | 9.6 |
| 87-08-20 | D | 60 | 37.5 | 42.1 | 55.2 | 3.8 | 6.9 |
| 87-06-22 | D | 60 | 42.1 | 46.6 | 57.8 | 7.4 | 8.5 |
| 86-11-07 | X | 65 | 35.7 | 46.8 | 52.9 | 6.0 | 8.0 |
| 86-11-07 | X | 62.5 | 39.3 | 50.9 | 53.4 | 4.7 | 8.4 |
| 86-10-29 | X | 65 | 34.4 | 52.3 | 66.2 | 6.2 | 8.1 |
| 86-09-10 | X | 60 | 40.9 | 43.0 | - | 6.7 | 7.7 |
| 86-09-03 | X | 60 | 35.7 | 41.0 | - | 5.7 | 6.8 |
| 86-07-17 | X | 60 | - | - | - | 5.6 | 9.3 |
| 86-07-04 | X | 60 | - | - | - | 5.0 | 9.2 |
| 86-05-26 | X | 60 | - | - | - | 4.0 | 7.0 |