Shotcrete: Recommended Practice for Repair of Highway Bridges

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BACKGROUND

Shotcrete, defined as mortar or concrete pneumatically projected at high velocity onto a receiving surface, has been used in the repair of highway bridges across Canada. Typically, shotcrete provides a more economical remedial solution for repair of surficial damage encountered in deteriorated bridges, compared to remedial work performed with formed and cast-in-place repair concretes, or hand-applied repair materials. The shotcrete process is best suited to the repair of overhead, vertical or steeply sloping surfaces. Gradually sloping or horizontal surfaces are generally more favourably repaired with cast-in-place procedures.

In 1990, C-SHRP commissioned a study to evaluate the durability of shotcrete rehabilitation treatments of bridges in Canada. The study was undertaken in recognition of the very limited data available on the long term performance of shotcrete structures in the field. Most durability data for shotcrete was the result of physical performance in laboratory freeze-thaw testing. At the time, most of the case history data provided only qualitative visual data with little physical quantification of the properties of layered concrete in the field. There was a wide variety of material being used for shotcrete in Canada and application procedures varied greatly between different areas. A need was perceived for information concerning the relative performance and service life of these different shotcrete treatments.

In order to evaluate the physical condition of shotcrete repairs, a total of 61 bridges in four provinces was examined, and the results of the survey are reported in Durability of Shotcrete Rehabilitation Treatments of Bridges in Canada. Photographic documentation and visual examination in the field were used to rate the overall condition of the repair of the bridges as excellent, good, fair, poor, or failed. Sixty-two percent of the repairs were considered to have performed well, being in good or excellent condition. Often, the downgrading of a rating to a lesser category could be attributed to poor workmanship, failure to eliminate the original cause of deterioration, or failure of the concrete behind the shotcrete patch. The graph in Figure 1 provides a breakdown of the condition of shotcrete rehabilitation treatments of the examined bridges.

The important conclusion of the survey was that for most patch-type shotcrete repairs, the longevity of the repair is largely dictated by the rate of continuing deterioration in the surrounding original reinforced concrete. Regardless of the relative merits of different shotcrete materials, very little deterioration of properly de-
signed, applied and cured shotcrete was found. For most structures, additional repairs will be required to the surrounding original concrete long before any remedial work is required on existing shotcrete repairs.

Following the survey, C-SHRP commissioned Dr. D.R. Morgan of HBT AGRA Limited in British Columbia to prepare a Recommended Practice for Shotcrete Repair of Highway Bridges. The document is based on the extensive professional experience of the author and other contributors and it represents the best current practice for the durable shotcrete repair of bridges. The Recommended Practice addresses deficiencies identified in the survey of shotcrete repairs regarding application techniques and resolution of original causes of deterioration. Highlights of the Recommended Practice are provided below.

RECOMMENDED PRACTICE FOR SHOTCRETE REPAIR OF HIGHWAY BRIDGES

Recommended Practice For Shotcrete Repair Of Highway Bridges is presented in three parts. The recommended practices for dry-mix and wet-mix shotcrete repair are the first and second parts, respectively. Although considerable duplication exists between these two sections, there are sufficient differences between them to warrant separate treatment. These sections are detailed and written in a "specification-style" format in order to assist the specifier in preparation of contract documents. Nonetheless, it should be remembered that the Recommended Practice is not a specification document as it contains guidance and recommendations for owners, engineers, and contractors. That guidance is provided under twelve categories, as follows:

1. General Description and Requirements
2. Submittals
3. Reference Standards
4. Materials
5. Shotcrete Proportioning
6. Supply and Equipment
7. Preparation for Shotcreting
8. Quality Assurance and Quality Control Testing
9. Safety and Clean-up
10. Shotcrete Application and Finishing
11. Curing and Protection
12. Shotcrete Acceptance and Repair

The third section of the Recommended Practice is a commentary which applies to both dry- and wet-mix processes, draws distinctions between them, and offers guidance in the selection of the appropriate process for a given project. The following sections summarize the comments beginning with overall design considerations for shotcrete repair.

DESIGN CONSIDERATIONS

The first decision in any shotcrete bridge repair project is whether to use the dry-mix or wet-mix shotcrete process. The dry-mix process is best suited to smaller volume repair projects particularly where there is considerable starting and stopping. In contrast, the wet-mix process is better suited to larger volume continuous shooting operations, with few interruptions. The dry-mix shotcrete process also tends to be better suited to predominantly overhead repair work because greater thicknesses are attainable in a single pass. In either case, to provide durable, long service-life repairs a number of design considerations, derived from the review of shotcrete repaired bridges, should be applied.

In the remedial design, every attempt should be made to protect the existing concrete and new shotcrete repairs from exposure to the cause of the original deterioration. Where the deterioration
has resulted from de-icing chemicals and frost action, preventive measures may include sealing, repair or replacement of bridge decks and expansion joints, red design of deck and abutment drainage systems, and repouring substructural elements such as pier caps and abutments to prevent ponding and facilitate drainage.

In many bridges it may be necessary to maintain full or partial traffic on the bridge deck during the remedial work. It may be difficult to effect quality repairs on elements which are subjected to continuous vibration or deflections from traffic during shotcrete operations. Careful consideration should be given at the design stage to possible traffic control measures or restrictions.

Some shotcrete repairs of bridges have been required because of general deterioration of the concrete matrix. In those cases, reliance should not be placed solely on the quality of bond of the shotcrete to original concrete for long-term performance of the repair. To avoid slabbing failure, it is important to tie back the repair shotcrete into the existing concrete, using appropriately designed anchors or the existing reinforcement.

Corrosion of embedded reinforcing steel and subsequent spalling in the original concrete has necessitated shotcrete repairs of many bridges. In many instances, corrosion has resulted from a lack of adequate cover to reinforcing steel. In such repairs it is important that all spalled, deteriorated and delaminated concrete be removed. Also, concrete should be removed and replaced in areas displaying high reinforcing steel corrosion activity.

In many severely corroded bridge elements, it may be necessary to remove and replace or supplement existing reinforcing steel with additional reinforcement. Some older bridges may be inadequately reinforced by current design standards. Additional reinforcement can be included as part of the designed repair. Fibre reinforcement can be effectively used in some structures in place of reinforcing mesh, but not in place of primary reinforcing steel. Fibre reinforcement can be very effective in minimizing thermal and shrinkage induced cracking in the shotcrete repair. It also provides increased toughness and impact resistance.

In repair of deteriorated load-bearing elements it may be necessary to conduct the repair work sequentially, in order to not compromise the safety of the structure. In those cases, work should be done under the supervision of an engineer, and may require that partial concrete removal, preparation and shotcreting be completed in repair of a bridge component prior to removal of more material.

The design should prohibit featheredging of shotcrete repairs or the application of skimcoats of shotcrete to unprepared original concrete surfaces. Such repairs have a high occurrence of failure in the field.

Where considerable thicknesses of shotcrete are to be applied, particularly in overhead applications, consideration should be given to the use of dry-mix, silica fume shotcrete, rather than conventional or latex-modified shotcrete. Wherever possible, shotcrete should be applied in a single lift, rather than in multiple layer construction; dry-mix silica fume shotcrete is better suited to single lift construction than any of the other types of shotcrete.

In repair of structural elements such as piers, abutments and parapets, the element should be completely capped with shotcrete. If the shotcrete repair does not cap the element, it may act as a "dam" and promote saturation of the original concrete with water and salt solutions which can accelerate the deterioration of the original concrete.

Finally, the designer should consider the aesthetic requirements for the shotcrete repairs. The particular type of shotcrete used and the type of finish selected will affect aesthetics. The most economical finish is the as-shot, gun finish. This may suffice for many structures with low visibility or on secondary highways, but may not be satisfactory for bridges in city areas or on primary highways, where visual aesthetics and public perception are important.

**MATERIALS**

A number of recommendations are made in the *Recommended Practice* about the materials, including cement, water, aggregate, admixtures, and reinforcement, that are used in shotcrete repair of bridges.

Most shotcrete repair of bridges is carried out with CSA Type 10 or 20 Portland cement. High early strength concrete may be specified in some situations, such as trafficked bridges. Supplementary cementing materials may include pozzolans or silica fume. The lat-
ter is by far the most widely used supplementary cementing material and is used in both wet and dry-mix shotcrete for the benefits it imparts to both the plastic and hardened shotcrete.

It is important that all mix water used in shotcrete preparation and production processes be of drinking water quality. Water used in preparation of concrete surfaces should be free of mud, oil or other contaminants which might interfere with shotcrete bond.

Only good quality, hard, dense aggregates conforming to all the requirements for concrete aggregates should be allowed in shotcrete. In particular, the use of frost-susceptible or alkali-reactive aggregates should be avoided, in view of the aggressive exposure conditions to which most shotcrete repairs are subjected. Recommended aggregate gradation limits for nominal 10 mm and 5 mm maximum size aggregate gradations are given in the Recommended Practice.

The use of admixtures is generally not required in dry-mix shotcrete, with the possible exception of the addition of air entraining admixture. Extensive research has shown that freeze-thaw durable dry-mix shotcrete can be produced without the addition of air entraining admixtures, provided the shotcrete is properly proportioned, applied and cured. In wet-mix shotcrete the use of air-entraining admixtures is considered mandatory for shotcrete exposed to freezing and thawing. The use of water-reducing admixtures is generally recommended for wet-mix shotcrete, as they reduce the water demand of the shotcrete, thus helping reduce shrinkage. For silica fume-modified wet-mix shotcretes the use of a superplasticizing admixture is strongly recommended, in order to control water demand and hence strength and shrinkage of the mixture.

Placement of reinforcing steel for shotcrete applications differs from conventional concrete reinforcing steel installation requirements in that the bars should always be spaced and arranged to facilitate shotcrete placement and to avoid the formation of sand pockets and voids. Welded wire mesh fabric is commonly used in shotcrete repair of bridges to mechanically tie back the shotcrete to fixed anchors or existing reinforcement and to enhance the resistance of the shotcrete to thermal and drying shrinkage induced cracking. fibre reinforcement can be used in lieu of mesh reinforcement, but it should be properly mechanically anchored to the existing concrete, using anchors with appropriate shear connectors. Anchoring along the perimeter of the repair is particularly recommended. The use of steel fibre reinforced shotcrete is advantageous, compared to mesh reinforcement, in that eliminates the requirement for fixing mesh and the difficulties which can sometimes be encountered in fully encasing mesh.

SHOTCRETE PROPORTIONING

The onus for shotcrete mixture design should be placed on the contractor, who is expected to have adequate experience to be able to submit suitable mix designs and performance documentation. In the absence of such experience, a number of "starting mix" designs are provided in the Recommended Practice.

Silica fume is typically incorporated into shotcrete at addition rates between 8 and 15% by mass of cement. Addition rates of 8% will often suffice for repair of predominantly vertical or sloping surfaces. Addition rates of 12% are preferred for predominantly overhead surfaces. In bridges subjected to vibrations, or repair in wet areas, it may be necessary to increase the silica fume content to as much as 15% in order to prevent loss of freshly placed shotcrete.

Recommended performance requirements for shotcrete repairs are given in the Recommended Practice. These specify a maximum water/cementitious materials ratio of 0.4 for most strength and exposure conditions. Minimum compressive strengths of 30 MPa after seven days and 40 MPa after 28 days are required. Higher compressive strengths can be specified if required for structural reasons. Specification of maximum limits on the permissible values of boiled absorption (8%) and volume of permeable voids (17%) has proven useful as a measure of shotcrete quality. The Rapid Chloride Permeability Test has been adopted by some agencies as a quality control measure for shotcrete. It provides an indication of the chloride ion intrusion inhibiting characteristics of the shotcrete. The recommended limits of 1000 coulombs for silica fume shotcrete and 1500 coulombs for latex-modified shotcrete can normally be readily achieved in the field.

SUPPLY AND EQUIPMENT

Site-batching of dry-mix shotcrete, using either volumetric or mass batching equipment can be
use for shotcrete bridge repair. The volume of shotcrete materials required for most bridge repair contracts is such that it is not normally expedient to establish stockpiles of shotcrete materials and batching facilities on site. Dry-bagged premix materials, or mobile, volumetric site batching are the preferred supply systems as they produce fresh shotcrete as needed, with minimal wastage. The use of rotary drum, transit-mix batched and supplied dry-mix shotcrete is not recommended.

There are a wide variety of dry-mix shotcrete guns for application. The most commonly used guns operate on a rotating barrel-feed system, but pressurized chamber type guns are also used. Large capacity air compressors are required to pneumatically convey the shotcrete materials down the line to the nozzle. Water is added partially through the use of damp aggregates with the remainder of the required mix water being added at a water ring at the nozzle.

Wet-mix shotcrete is essentially similar to conventional concrete in terms of batching, mixing, and supply. The most common systems are either central mix batched and transit mix supplied shotcrete, or transit mix batched and supplied shotcrete.

In the wet-mix system there are two basic different types of shotcrete application systems; the conventional or “thick-stream” method and the “thin-stream” method. The former method is most commonly used and typically uses conventional concrete-type pumps with air addition at the nozzle at the end of the delivery hose. The latter method normally involves the use of a pressurized chamber to pneumatically convey the shotcrete down the hose to the receiving surface. It is most suited to the application of mortar-like mixtures and has low productivity rates.

**PREPARATION FOR SHOTCRETING**

One of the most important aspects of shotcrete repair is proper preparation of the substrate. All areas of loose, spalled, delaminated or deteriorated concrete should be removed prior to shotcrete application. Concrete removal can be accomplished using a wide variety of mechanical tools, but the use of heavy duty equipment should be avoided. As an alternative to mechanical methods, high pressure water jetting hydrodemolition equipment can be used.

In preparation for shotcreting, reinforcement requirements can include replacement of existing corroded reinforcing steel, addition of new reinforcing steel, provision of shrinkage and temperature crack control reinforcement, and reinforcement to tie-back the shotcrete repair to the existing concrete. For corroded reinforcing steel, bars which display deep pits, or have lost more than 20% of their cross-sectional area, should be removed and replaced, or supplemented with additional reinforcement. Specific recommendations for the design of reinforcement are contained within the Recommended Practice.

**QUALITY ASSURANCE AND QUALITY CONTROL TESTING**

A suitable quality assurance program and a rigorous quality control testing program should be implemented to achieve a satisfactory end product. The recommended details for such programs are provided in the Recommended Practice.

**SAFETY AND CLEAN-UP**

During concrete removal and shotcrete application processes safety measures should be implemented to protect personnel from injury, and equipment and adjacent property from damage.

**SHOTCRETE APPLICATION AND FINISHING**

General recommendations for shotcrete application in bridge repair projects is provided in the Recommended Practice. Three issues which are important to the provision of quality shotcrete should be emphasized. First, suitable scaffolding or elevating devices should be provided to give the nozzleperson good access for proper nozzle orientation to the receiving surface. Second, sufficient ventilation and lighting are necessary to provide a clear, unhindered view of the shooting area. Third, predampeners should be used when applying dry-bagged premix shotcrete to minimize dust formation and enhance the homogeneity of the in-place shotcrete.

**CURING AND PROTECTION**

One of the most important requirements for a successful shotcrete repair is proper curing. The best means of curing is to keep the shotcrete continuously saturated with water for a minimum of four days, but preferably for
seven. This enables the shotcrete to gain strength before being subjected to pronounced drying shrinkage stresses. Means of accomplishing this are set out in the Recommended Practice.

In cold weather shotcreting operations it is recommended that shotcrete not be applied if the substrate concrete temperature is below 5°C. The air temperature in contact with the shotcrete should be above 10°C. Otherwise, setting and hardening of the shotcrete can be very slow and bond to the substrate could be damaged.

**SHOTCRETE ACCEPTANCE AND REPAIR**

A knowledgeable inspector should monitor the shotcrete application and any deficiencies observed during the shotcrete application process should be immediately addressed. Any defective shotcrete should be removed while it is still plastic. Otherwise, when shotcrete needs to be removed and repaired, the same basic procedures specified for original concrete repair should be followed.

**CONCLUDING REMARKS**

The highlights provided in this technical brief are not intended as a substitute for the Recommended Practice. Bridge-owning authorities and practitioners are urged to acquire the source document as it represents the best current practice for the durable shotcrete repair of bridges. It is believed that if remedial works are conducted rigorously in accordance with the procedures outlined in the Recommended Practice, bridge-owning authorities will be provided with durable shotcrete repairs, with service lives longer than surrounding non-repaired concrete.

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For full details of this research see:

**Durability of Shotcrete Rehabilitation Treatments of Bridges in Canada**
D.R. Morgan, J. Nell, Hardy BBT Limited, Burnaby, B.C.
Canadian Strategic Highway Research Program Transportation Association of Canada
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