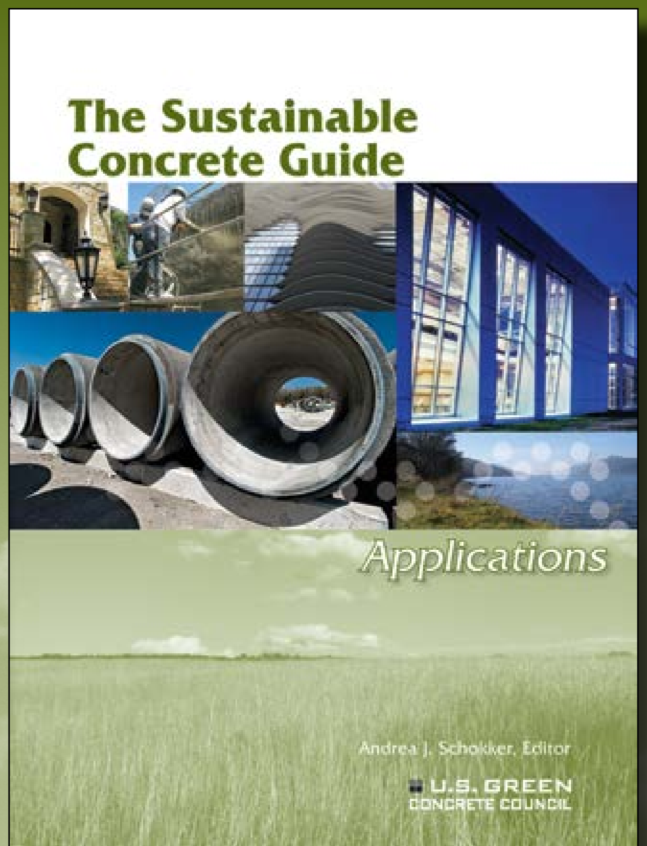
Sustainability of Shotcrete



This content was excerpted from the book: “The Sustainable Concrete Guide—Applications.” This newly published book is the companion resource to the “The Sustainable Concrete Guide—Strategies and Examples.” “The Sustainable Concrete Guide—Applications” provides readers with specific sustainable benefits of concrete’s various applications to assist in selecting/specifying concrete materials and products. Also included are tips and case studies on specifying concrete materials, constructing for sustainability, integrating into sustainable structures, and navigating green codes and standards. “The Sustainable Concrete Guide—Applications” was published by the U.S. Green Concrete Council, and is available from the American Concrete Institute at **www.concrete.org**.

Shotcrete

Architects, engineers, developers, and contractors are under ever-growing pressure to use more efficient methods in construction. Shotcrete construction has many unique characteristics that substantially increase the sustainability aspects of both new construction and repair. Shotcrete, as shown in Fig. 3.74, enables key savings in labor, materials, material handling and construction time, as well as providing increased flexibility and efficiency in shapes and thicknesses.

As shotcrete is simply a method for placing concrete, shotcrete enjoys all the sustainability advantages of concrete as a building material including use of recycled materials, SCMs, and the very broad topics related to durability, reparability, etc. The sustainability advantages unique to shotcrete are inherent in the placement process.

The recently published U.S. Green Concrete Council book *The Sustainable Concrete Guide—Strategies and Examples* lists five key aspects that improve sustainability of buildings. Shotcrete can impact each of these key aspects as follows:

Improving functionality—Increased functionality means a more efficient structure to serve its intended purpose. Shotcrete allows great flexibility in structural shapes and efficiency. Shotcrete can easily provide variable section thicknesses to allow various sections of the structure to exactly match the structural requirements without use of excess material. Shotcrete also allows the architect or engineer to easily create non-flat sections to provide smooth transitions in the structure and maximize the use of space.

Ensuring longevity—The longer the usable life of a structure, the less the need for repair or replacement of the structure that would entail using more resources. Concrete as a material, properly designed and constructed is unmatched in its ability to provide durable structures. Shotcrete matches the durability of concrete, and often allows existing concrete structures to be efficiently and economically repaired to provide extended life with much less use of resources when compared to new replacement structures.

Enhancing occupant comfort—A more comfortable environment within a building increases productivity of the users, and thus adds to the efficiency of the structure's overall use. Thermal mass of concrete and shotcrete can help moderate inside temperatures. Naturally light color and the ability to provide a variety

Fig. 3.74—Shotcrete application. *Photos courtesy of American Shotcrete Association*

of finishes to exposed concrete surfaces can help to enhance natural lighting, and reduce use of other finishing materials. Shotcrete finishes can range from a smooth plaster-like finish to a faux-rock surface that looks like natural rock.

Reducing the use of resources—Reduction or elimination of formwork saves the natural resources needed to make the form and supporting structure (wood or steel), as well as the resources to move the formwork to and on the site. Additionally, concrete used in shotcrete is great for reusing many recycled materials, including supplementary cementitious materials such as fly ash or slag, or reused aggregates from crushed concrete. The ability to increase recycling means less material that ends up taking space in landfills and is essentially lost to future use. Also, the long-term durability of concrete means a much longer replacement cycle is needed, and thus resources are not used nearly as often as with other construction materials. The ability to provide variable thickness to exactly match the structural thickness means less material is needed.

Aesthetics—This aspect addresses the social component of sustainability. Visually pleasing structures can give an increased sense of community pride. Shotcrete can produce virtually any shape. It is like clay that an architect or engineer can mold to their creative vision. Combined with the wide variety of finishes available, the aesthetics of shotcrete are extensive and still provide the durability of concrete.

Specific Sustainability Aspects of Shotcrete

Formwork Reduction or Elimination

A detailed listing of the sustainability advantages of shotcrete is included in Table 3.4. Reviewing the table, the first and one of the most significant advantages are realized in formwork material savings. With the shotcrete process, the material is gunned or sprayed in place, so forming becomes unnecessary or is reduced by 50% with the use of one sided forms. This not only reduces or eliminates the amount of wood or other material used in forming, but also reduces or eliminates the milling and transportation environmental impact involved in providing the lumber on thousands upon thousands of construction sites. Where one-sided forms are required, the formwork design is greatly simplified and the materials required are significantly reduced because there is no need to design for internal pressure from fluid concrete within a form.

In overhead work, not only is the formwork eliminated, but the scaffolding and shoring required to support overhead forms is eliminated. This means less on-site labor, as well as on-site equipment to unload, move and load for shipping the forming and shoring materials.

In addition to the formwork materials resource savings, there is a tremendous amount of labor involved in the forming operations. Using shotcrete reduces or totally eliminates time and money expended on the building of forms, whalers, bracing, forming support structures, and the application of release agents. Due to the natural consolidation of concrete when placed via shotcrete, consolidation operations are also eliminated. Post placement formwork labor, including items such as form tie hole patching and cleaning of forms, are also significantly reduced or eliminated.

Construction Efficiency

This leads us to the closely related, but perhaps not as initially obvious, advantage of construction sequencing efficiency. The elimination of half or all formwork and its related operations, paired with the speed and flexibility of the placing of concrete via shotcrete, creates significant opportunities for reducing the construction time of a project. With new construction, the use of shotcrete to place vertical or overhead concrete surfaces often results in a time savings of 33 to 50%. Labor savings alone on repair applications can easily reach 50%.

Repair and Rehabilitation

The last area of note is repair or rehabilitation. Shotcrete is an excellent repair option for existing concrete structures. There are often times, when shotcrete is the only economically or logistically possible option due to limited or restricted access to use normally formed and cast concrete sections. Chapter 25 also includes additional information regarding the use of shotcrete in repair applications.

Creativity and Efficiency of Shotcrete Sections

Most normal formed and placed concrete uses flat surfaced shapes, as these are by far the easiest to form. Curved or even just tapered sections may be used in form and cast work, but the formwork is much more expensive to construct both in labor and materials. Using shotcrete allows total flexibility in shape and surface treatment. Variable thicknesses, curves, or virtually any combination of shapes are readily available to the designer who uses shotcrete construction without any of these additional formwork or labor costs. This is why shotcrete is used for free-form pools, faux-rock surfaces for fountains and zoo enclosures, and tapered walls of liquid storage concrete tanks.

Because the finished shotcrete surface is available immediately when placed, there is no question what the final finish will look like. Also, the finish is limited only by the creativity of the architect or engineer and the talents of the shotcrete contractor.

Summary

Shotcrete offers an exceptional number of placement sustainability advantages, while still enjoying all the sustainability advantages of the concrete material, for both new construction and repair/rehabilitation operations. This 100-year-old process offers the opportunity for

Shotcrete Top Sustainability Benefits

- Crane and other equipment savings or elimination.
- Labor savings of at least 50% in repair applications.
- New construction speed savings of 33 to 50%.
- Better bonding to the substrate enhances durability
- Adaptability to repair surfaces that are not cost-effective with other processes.
- Ability to access restricted space and difficult-to-reach areas, including overhead and underground.
- Complex shapes require very little, if any, formwork.
- Formwork does not have to be designed for internal pressures.
- Material savings through elimination/reduction of formwork.
- Speed of repair reduces or eliminates downtime.

material, labor and speed savings, all of which are critical sustainability advantages. Table 3.4 summarizes benefits/advantages of shotcrete.

Case studies

Atlantic Times Square Project, Monterey Park, CA

This large, mixed-use development project had an extremely tight construction schedule—the contractor had to place walls very quickly. As shown in Fig. 3.75, shotcrete provided the solution: walls used one-sided formwork, shotcrete was applied, and then the free surface was finished by hand. Forms were then moved to the next wall and reused. With a trailer pump on site twice a week, between 80 and 130 yd^3 (61 and 99 m^3) of concrete could be shot in an average 8- to 10-hour day.

The scale of the project was immense, with over 230,000 ft^2 (21,400 m^2) of retail and entertainment space that stretches a full city block adjacent to I-10. It includes three levels below grade, and six levels above grade. Traditionally, the walls would be cast-in-place concrete or masonry, but the contractor chose the speed of shotcrete for all of the concrete walls (interior and exterior) on the project. The reuse of forms and the need for only one formed face per wall also contributed to reducing the environmental impact. With crews working only from one side of the wall, congestion on the job site was also reduced.

Surrey 2010 Olympic Games Preparation Center, Vancouver, BC, Canada

This center played a prominent role in the 2010 Olympic Games in Vancouver as a training venue for Olympians and volunteers, as well as a central location for all recruitment and logistics. The project got off to a late start, so shortening construction time as much as possible was critical. The structure was architecturally intense, with curved top walls up to 40 ft (12 m) high and extensive reveals, recesses, and block-outs. The specified finish was a light sandblast and two coats of clear sealer, so quality finish was essential. The project

Fig. 3.75—Placing shotcrete at the Atlantic Times Square Project in Monterey Park, CA. *Photo courtesy of American Shotcrete Association*

Table 3.4—Summary of shotcrete sustainable attributes

Shotcrete sustainability benefits/advantages	Carbon footprint reduction	Thermal transmission (*R*-values)	Thermal mass and operational energy	Longevity and life cycle	Storm-water management	Human factors and the living/working environment	Security and safety	Reduce, reuse, recycle	Economic impact	Resilience with respect to climate change	Compatibility with other innovative sustainability strategies
Recycled materials: same usage/benefits as cast-in-place concrete		**Same as concrete**	**Same as concrete**							**Same as concrete**	
Silica fume	X	—	—	X	—	—	—	X	—	—	X
Fly ash	X	—	—	X	—	—	—	X	X	—	X
Slag cement	X	—	—	X	—	—	—	X	X	—	X
Recycled aggregate—crushed brick use in refractory applications	X	—	—	X	—	—	—	X	X	—	X
Use of rebound in other applications: for example, soil stabilization, use in other products (for example, form blocks—aggregate)	X	—	—	X	—	—	—	X	X	—	X
Portland cement substitutes											
Limestone cements	X	—	—	—	—	—	—	X	X	—	X
Metakaolin	X	—	—	—	—	—	—	—	—	—	X
Wood/formwork material savings											
At least 50% savings, 100% on some applications. Repair is also 50 to 100%.	X	—	—	X	—	—	—	X	X	—	X
Wood and/or metal material savings	X	—	—	—	—	—	—	X	X	—	X
Transportation/milling cost savings	X	—	—	—	—	—	—	X	X	—	X
Disposal of used form material	X	—	—	—	—	—	—	X	X	—	X
Cleaning of forms	X	—	—	—	—	—	—	X	X	—	X
Reduction/elimination of form release agents' use	X	—	—	—	—	—	—	X	X	—	X
In one-sided forms—reduced thickness of form	X	—	—	—	—	—	—	X	X	—	X
Formwork does not have to be designed for internal pressures	X	—	—	—	—	—	—	X	X	—	X

Table 3.4—Summary of shotcrete sustainable attributes, cont.

Some one-sided forms can stay in place after construction	—	—	—	—	—	—	—	X	X	—	X
Complex shapes require very little if any formwork	X	—	—	—	—	—	—	X	X	—	X
Mining/tunnels—no formwork required	X	—	—	—	—	—	—	X	X	—	X
Crane time savings or elimination	X	—	—	—	—	X	—	X	X	—	X
Bracing savings/elimination	X	—	—	—	—	—	—	X	X	—	X
Speed/labor savings—(calculation or multiplier)											
Labor savings of approximately 50% in repair applications	X	—	—	—	—	—	—	—	X	—	X
New construction—speed savings of 33 to 50% (examples of savings)	X	—	—	—	—	—	—	—	X	—	X
Shortened construction time occupancy/access after repair	X	—	—	X	—	X	—	—	X	—	X
Usability in new construction	—	—	—	—	—	—	—	—	X	—	X
No form ties	X	—	—	—	—	—	—	—	X	—	X
No form tie hole patching	X	—	—	X	—	—	—	—	X	—	X
Walls are in final finish after shooting	X	—	—	X	—	—	—	—	X	—	X
Sequencing time savings/advantages—fill scheduling gaps with shotcrete placement	X	—	—	—	—	—	—	—	X	—	X
Reduced man hours	X	—	—	—	—	X	—	—	X	—	X
Economic impact											
Mixture design advantages resulting from placement compaction—thinner sections	X	—	—	X	—	—	—	X	X	—	X
More efficient and thinner structural sections—repair and new construction	X	—	—	X	—	—	—	X	X	—	X
Overall/bottom line savings due to time savings and reduced direct construction costs	X	—	—	—	—	—	—	X	X	—	X
Repair/strengthening/rehabilitation	—	—	—	—	—	—	—	—	—	—	—
Minimal (if any) formwork	X	—	—	X	—	X	—	X	X	—	X

Table 3.4—Summary of shotcrete sustainable attributes, cont.

Speed of repair reduces or eliminates downtime	X	—	—	X	—	X	—	X	X	—	X
Preservation of structures that could not otherwise be repaired	X	—	—	X	—	X	—	X	X	—	X
Seismic retrofits	X	—	—	X	—	X	X	X	X	—	X
Better bonding to the substrate—will enhance durability	X	—	—	X	—	—	—	—	X	—	X
Adaptability to surfaces that are unrepairable with other processes	X	—	—	X	—	X	—	X	X	—	X
Overhead placement quality and efficiency	X	—	—	X	—	—	—	—	X	—	—
Ability to access restricted space and difficult-to-reach areas	X	—	—	X	—	X	—	X	X	—	—

Table courtesy of American Shotcrete Association

was planned assuming 24/7 production to increase the chances of completing the project in the 6-week allotted time period (one quarter of the time typically allowed for this type of structure). Shotcrete was an integral part of the success of the project in terms of schedule and quality. The time from the first excavator bucket hitting the ground until structural completion was 3-1/2 weeks, without the need for 24/7 production or even the need for a second shift. The speed of construction was even more remarkable considering the 50-year record-breaking snowfall with up to 3 ft (0.9 m) of snow and subzero weather conditions for the entire duration of the project. All vertical portions of the project were placed with shotcrete, including the structural walls, building envelope, and architectural features. The tall walls were formed on one side to full height (up to 40 ft [12 m]); the use of shotcrete with one-sided forming on such tall walls with multiple block-outs reduced the amount of formwork to one-sixth of what would have been needed on a traditional placement. Figure 3.76 shows the center under construction.

CEMEX Bayano Plant No. 2 Line Expansion, Panama

CEMEX is one of the world's two largest cement companies, with a production capacity of approximately 86 million tons (78 million metric tons) of cement per year. In 2007, CEMEX announced it would construct a new kiln at its Cemento Bayano, S.A. plant in Panama to help meet the anticipated demand for additional cement due to the Panama Canal expansion project (a massive project expected to cost approximately $5.25 billion USD). As shown in Fig. 3.77, the Bayano plant, with the new expansion, has become one of the most modern, efficient, and environmentally friendly cement production facilities in the Americas. The plant expansion included construction of a 77,000 ton (70,000 metric ton) capacity clinker storage facility. Domes provide efficient and economical storage, and have become popular with major cement producers. Advantages include better containment and protection of stored materials, efficient use of land, strength, durability, and rapid construction.

For the Bayano dome, a ring pile cap was constructed that formed the base ring. A fabric form was attached to the base ring and inflated. The fabric was a durable single-ply roofing material that remains in place after completion of the dome to function as the finished roof membrane. After the form was inflated, a 2 in. (50 mm) layer of polyurethane foam was applied against the form's interior surface, and initial reinforcement steel is attached using fasteners embedded in the foam. All work was done in the controlled environment inside the dome. The first layers of shotcrete are sprayed to provide stiffness and strength to support the next mat of heavier structural reinforcing bars. As the shell thickness increased, heavier layers of shotcrete were applied in a single pass. Shotcrete was applied overhead in thinner layers than shotcrete applied to a vertical surface. The project was completed in approximately 4 months (on time and on budget).

Fig. 3.76—The Surrey Olympic Games Center during construction. *Photo courtesy of American Shotcrete Association*

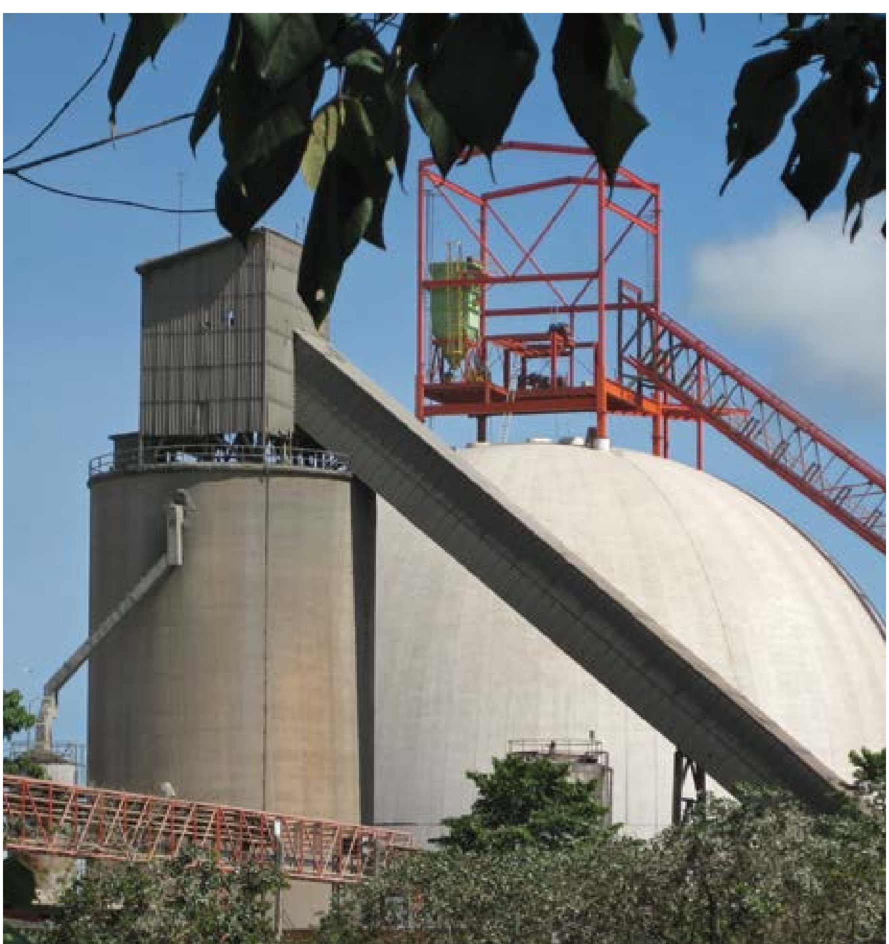


Fig. 3.77—CEMEX Bayano Plant No. 2 Line Expansion, Panama. *Photo courtesy of American Shotcrete Association*

Nozzleman—The craftsman that physically directs the placement of the shotcrete. The nozzleman is responsible for the quality of the placed shotcrete, and is an important member of a shotcrete crew. The nozzleman must have an understanding of the equipment's operation, safety procedures, and the material being placed. Critical to all applications of shotcrete is the knowledge and skill level of the nozzleman placing the shotcrete. In assessing nozzleman competency, a two-step qualification process has evolved. The ACI Shotcrete Nozzleman Certification is the industry-recognized credential for identifying individuals who possess the basic knowledge and skill level needed to apply shotcrete. For heavily congested projects, the nozzleman should possess current ACI Certification and be required to shoot test panels that simulate project conditions.

Nozzleman Certification is only one part of a larger process to secure a qualified and experienced shotcrete contractor. The process of qualifying a shotcrete contractor should include a thorough check of the shotcrete contractor's references and project work history, a thorough check of the project work history of the contractor's key personnel, and resumes of nozzlemen that are to participate on the project. Finally, current ACI Certification should be verified for the on-site nozzlemen.

Shotcrete—A process where concrete material is conveyed through a hose and pneumatically projected at high velocity onto a surface to achieve compaction. Shotcrete is used primarily in the construction of vertical and overhead surfaces. This process allows construction of walls and other structures using only a one-sided form. Tanks, swimming pools, tunnels, mines, sculptured rocks, structural walls, erosion control embankments, retaining walls, and shearwalls are all structures commonly built using shotcrete. In addition, a wide variety of repairs are done with shotcrete.

Dry-mix shotcrete—The process illustrated in Fig. 3.78 in which a dry mixture of cementitious materials and aggregates is conveyed pneumatically through a delivery hose at the end of which water is injected at a nozzle. All ingredients, except water, are thoroughly mixed together before being conveyed through the delivery hose. The cementitious materials and aggregate mixture is fed into a special mechanical feeder or gun, called the delivery equipment. The material is then carried by compressed air through the delivery hose to a nozzle body. The nozzle body has an interior water ring, where water is introduced under pressure and thoroughly mixed with the other ingredients. The material is shot from the nozzle at high velocity onto the receiving surface. Mixing occurs in the nozzle and as the material impacts the surface.

Gunite—A term that refers to dry-mix shotcrete. The term was once a proprietary trade name, but became a generic name in 1967.

Wet-mix shotcrete—The process illustrated in Fig. 3.79. It has all the ingredients—including cement, chemical and mineral admixtures, aggregate, and mixing water—thoroughly mixed together before being pumped into a delivery hose or pipeline. Compressed air is added at the nozzle to increase the material velocity. The mortar or concrete is then shot from the nozzle at high velocity onto the receiving surface.

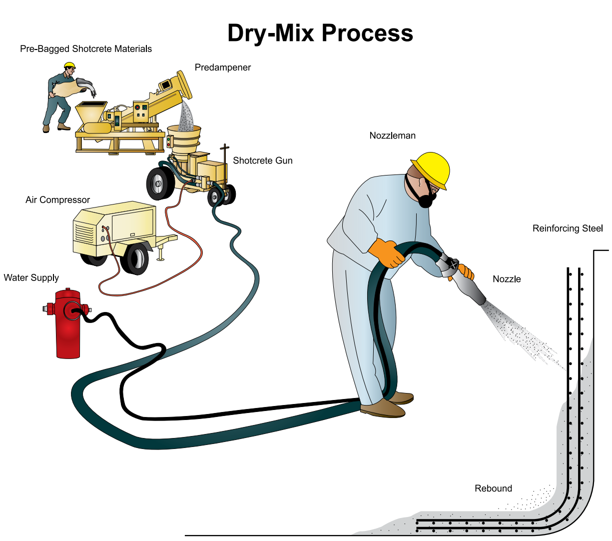


Fig. 3.78—Dry-mix shotcrete process. The dry mixture is conveyed pneumatically through the delivery hose, and water is added at the end nozzle. *Photo courtesy of American Shotcrete Association*

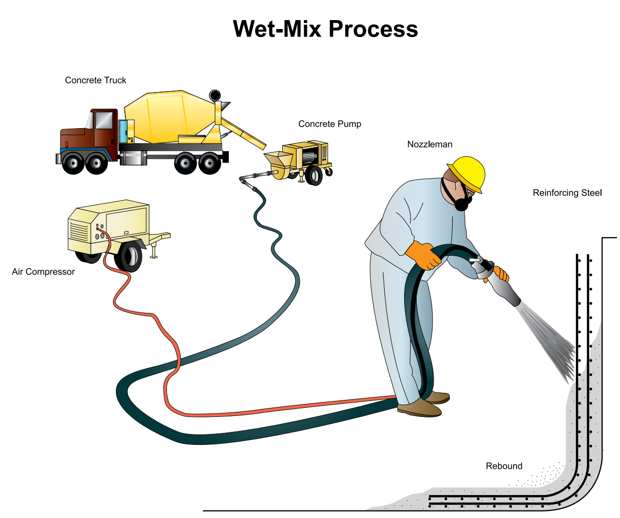


Fig. 3.79—Wet-mix shotcrete process. All ingredients are mixed together before being pumped through the delivery hose. Compressed air is added at the nozzle. *Photo courtesy of American Shotcrete Association*

Maintenance and repair

Shotcrete

Shotcrete is discussed in more detail in Chapter 21 in Part 3 on applications, but shotcrete has substantial benefits for enhanced sustainability in the repair industry as well. Shotcrete is an efficient repair method that offers significant material, labor and speed advantages in many repair applications; all of which are critical sustainability advantages.

Using shotcrete allows the repair contractor to economically and efficiently address a wide range of concrete repairs with these sustainability benefits:

- Use minimal if any formwork;
- Excellent bonding, eliminating the need for bonding agents;
- Allow unique overhead placement quality and efficiency;
- Increased speed of placement;
- Ability to provide custom finishes to the exposed shotcrete surface;
- Ability to provide the precise shape and thickness required for the structural or aesthetic functionality of the repaired concrete members;
- Gives the ability to access restricted or difficult to reach areas that may not be able to be repaired by normal form and pour methods;
- May eliminate or at least reduce shoring and scaffolding that would be needed for form-and-pour repair methods.
- May eliminate the need for heavy lifting equipment or forklifts on the site that would be needed for form-and-pour methods to build, set, and strip formwork.

As an example of shotcrete's inherent ability to facilitate a concrete repair, consider a concrete structure that has concrete cover that has spalled or deteriorated. The damaged concrete is removed, leaving an exposed surface of good-quality concrete and reinforcement. The shotcrete can then be shot directly onto the newly exposed surface without requiring forming or bonding agents. In addition to significant sustainability benefits from material resource savings by eliminating formwork, the use of shotcrete can result in a labor savings of up to 50% on a repair project. The shotcrete process offers all the sustainability advantages of concrete as a repair material, plus a significant number of sustainability advantages inherent in the placement process.

The seismic retrofit of the University of Memphis' Cecil C. Humphreys School of Law is included in the case studies section at the end of this chapter as an example application.

Securing reinforcing bar in chipped area prior to shooting.

Shooting of prepared area.

Case study

Cecil C. Humphreys School of Law, University of Memphis, Memphis, TN

The Cecil C. Humphreys School of Law is housed in the historic structure that once housed Memphis Customs, the Federal Court House, and the Post Office (Fig. 4.18). The 140,000 ft^2 (13,006 m^2) building was originally built in the early 1880s, and had several additions during the early 1900s. The granite, marble, and limestone used in the building had held up well, but the building needed to be retrofit to meet earthquake building codes. The building sits near the New Madrid Fault Line, known for a series of major earthquakes in the early 1800s.

The original 1880 building core required the most serious retrofit. Shotcrete was chosen for the massive shear walls and other additions needed. No. 8 (25M) steel reinforcing bars were constructed on a new footing in the basement floor, and then covered with 12 in. (304.8 mm) of shotcrete to create the reinforced concrete shear walls. The 4 ft (1.22 m) wide footer was built with a depth of 4 or 6 ft (1.22 or 1.83 m) to meet the design specifications. During the construction of the steel-reinforced shear walls, mounting plates and dowels were carefully placed for the location of the new floors. Within the building's rectangular core, a 3 ft (1 m) area was demolished around the perimeter of the existing floors to provide access to the walls of the steel reinforcing bar that connected the separate levels of the building. The completed internal shell of reinforcement steel and shotcrete provided the structure with enough strength to allow for the removal of the pre-existing flooring and support beams. The roof above the building's rectangular core was demolished to provide access to the interior levels. Large cranes used wrecking balls to demolish the old horizontal floor of arched brick and concrete around the steel support beams. The old beams were connected to the crane, and then cut to be lifted away just before the new steel I-beams were installed at each level. The new floor plans included auditorium seating in the large classrooms, so they required slanted support beams at varying heights. The accurate placement of the end plates during the shotcrete process was critical to the I-beam installation. The application of shotcrete allowed for minimal forming for the 12 to 20 ft (3.66 to 6.1 m) tall shear walls and ease of access for multiple contractors working on the project (Fig. 4.19).

Shotcrete's minimal forming allowed large areas to be prepared with reinforcing bars in advance of the shotcrete placement. The large historical building with multiple levels and an existing floor plan created many challenges during this project, but the use of shotcrete allowed the seismic retrofit to have minimal impact to the building's appearance. The Cecil C. Humphreys School of Law is a modern learning environment in a historical building, and the use of shotcrete helped to ensure a safe environment for many years to come.

Fig. 4.18—University of Memphis' Cecil C. Humphreys School of Law following the renovation project. *Photo courtesy of Lindsey Lissau*

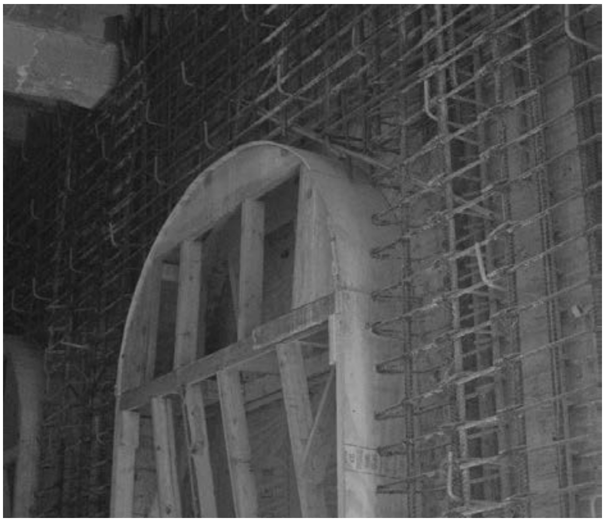


Fig. 4.19—Interior wall in preparation for shotcrete application. *Photo courtesy of American Shotcrete Association*

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