Is Shotcrete Sustainable?

By Lihe (John) Zhang

The shotcrete process was developed over 100 years ago. From the first cement gun made by Carl Akeley in Chicago in 1909, to the robotic spray arms now used all over the world, shotcrete has developed into a sophisticated technology with continuing advances in materials process, including mixture design optimization, shotcrete batching and production, transportation and application, and quality management systems. Shotcrete technology has gradually built up its reputation as a viable construction methodology through integration of new technologies, including the use of supplementary cementitious materials (SCMs), and new generations of chemical admixtures and fiber reinforcement. Shotcrete provides a unique process for applying concrete materials for ground support for both aboveground and underground new construction, repair, and retrofit. It has been proven to be an economic and technically effective system. This article briefly visits the history of shotcrete technology development from a sustainability point of view and attempts to answer the fundamental questions: Is shotcrete now sustainable, and if so, how can shotcrete be made more sustainable? This article further explores sustainability developments in the shotcrete industry based on decades of project experience, technology advancements, and the optimized use of resources. This article also attempts to quantify the merits of using shotcrete from a LEED point perspective.

Sustainability and Green Building

Sustainability is typically referred to as a development "that meets the needs of the present without compromising the ability of future generations to meet their own needs."[1] The definition of sustainability, green building, or sustainable development for buildings and construction is not universally agreed upon, but it is commonly accepted in industry that sustainability means the reduction, reuse, and recycling of resources and energies, reducing the carbon footprint (that is, CO_2 emissions), and minimization of environmental impact while improving the functionality of buildings. Technologies and construction methods related to sustainability include: 1) green cement and concrete technologies, including operation and production with a reduced carbon footprint, performance-based concrete mixture designs, use of SCMs, thermal transmission of concrete, longevity and life-cycle assessment, and stormwater management; and 2) construction methods that help to reduce social, environmental, and economic impacts while keeping construction activities safe and secure.

There are rating systems developed to evaluate a concrete structure's success in meeting predefined goals related to sustainability. These rating systems include LEED (**www.usgbc.org**), Green Globes by the Green Building Initiative (**www.thegbi.org**), and Green Ready Mix Plant Certification Program (**www.nrmca.org**). The most widely used standard related to shotcrete is, however, the LEED point system. Brief instructions regarding the LEED system, especially the related rating points and historical background of green building and concrete, can be found in another article in this magazine.[2]

Review of Shotcrete in Terms of Sustainability

Shotcrete is defined by ACI 506R-05, "Guide to Shotcrete,"[3] as concrete (or sometimes mortar) conveyed through a hose and pneumatically projected at high velocity onto a receiving surface. While the material component of shotcrete is essentially concrete, the process of shotcrete application is unique. It involves pneumatic projection of the concrete materials at high velocity so that compaction is achieved on the receiving surface. It is therefore necessary to review the materials and mixture design, admixtures and additives, application process, and durability for shotcrete with respect to sustainability. Appendix A provides a comprehensive list of advancements in shotcrete technology during the past century. Based on a review of these developments, it is proposed to answer the basic question: Is shotcrete sustainable?

Green Cement and Concrete

One of the most advanced green technologies in the shotcrete industry is the addition of SCMs such as fly ash, slag, silica fume, and metakaolin, to replace cement. Production of 1 ton of cement is accompanied with the emission of about 1 ton of CO_2. Most SCMs are industrial by-products or waste. Replacing cement with SCMs reduces the cement content of the mixture and therefore reduces CO_2 emissions.[1] Although replacing cement with SCMs does not achieve a carbon neutral state, that is, zero carbon emission, it does reduce the overall carbon footprint. The current LEED rating system grants one credit for 7.5% replacement and two credits for 15% replacement of cement with SCMs.

Besides carbon footprint reductions, the benefits of adding SCMs have been widely acknowledged by the building and construction industries. These advantages include: 1) improved workability for fresh shotcrete: for example, silica fume can be added to improve cohesiveness, adhesion, and thickness of buildup for overhead applications; and fly ash can be added to improve pumpability; 2) improved strength; and 3) improved durability such as reduced permeability, increased chemical resistance, and mitigation of potential alkali-aggregate reaction.

Performance-Based Design with SCMs

Most current shotcrete specifications tend to be performance-based instead of prescription-based. ACI Committee 506[3,4] is working toward predominantly performance-based specifications. A typical performance-based shotcrete specification is as follows:

Fly ash has been widely used in shotcrete mixtures for the merits primarily of workability and durability that it imparts, but this also provides sustainability. Fly ash is a waste by-product from the burning of coal for power generation. Traditionally, a large portion of fly ash has been used for landfill. Landfill and storage of fly ash is always also associated with high costs and, most importantly, a negative impact on the environment. The reuse of fly ash reduces the costs of landfill and storage, and further minimizes environmental impact. For cast-in-place concrete, fly ash is typically added at between 20 to 50% by mass of the total cementitious materials. For shotcrete, fly ash is typically added at between 15 to 20% by mass of the total cementitious materials. Requirements for a typical shotcrete mixture design with fly ash are listed in Table 1.

Silica fume has been found to provide superior performance for both concrete and shotcrete. Silica fume is typically added at 8 to 10% by mass of cement. Silica fume improves the cohesiveness of the fresh shotcrete, that is, it makes the shotcrete stickier. For overhead applications and vertical applications where stickiness is a requirement, adding silica fume is one of the best solutions. Although dry-mix shotcrete benefits the most from silica fume addition, using silica fume in wet-mix shotcrete is also beneficial. Silica fume improves compressive strength, permeability resistance, and durability. Silica fume-modified shotcrete mixtures are widely used in bridge retrofits, marine structure repair, and for underground support in tunnels and mines.

Metakaolin is a new SCM and it produces concrete and shotcrete that is intermediate in performance between fly ash and silica fume in terms of strength improvement. Metakaolin is a mined product and is typically added at between 10 to 20% by mass of cement. Metakaolin improves the cohesiveness of fresh shotcrete and the later-age strength development of shotcrete. It was first used in shotcrete on a mining project in British Columbia, Canada, in 2008.[4]

Other green technologies include limestone binary cement technology, but it has yet to be tested in shotcrete. Recycled aggregate has been tried in shotcrete but it is less promising due to its high variability in quality.[5]

Air Entrainment for Both Wet- and Dry-Mix Shotcrete

Air entrainment of wet-mix shotcrete improves pumpability and, most importantly, is very effective in improving resistance to freezing and thawing. For wet-mix shotcrete, an air content of 6 to 9% at discharge from the concrete truck into the shotcrete pump normally results in an in-place shotcrete with 3 to 5% air content. For dry-mix shotcrete, an air-entraining admixture can be

Table 1: Requirements for a typical shotcrete mixture design with fly ash

Target requirements	
Minimum compressive strength	5076.3 psi (35 MPa) at 28 days
Slump	2.4 to 3.1 in. (60 to 80 mm)
Maximum water-cementitious material ratio (*w/cm*)	0.40
Air content	4 to 5% as shot
Maximum size of aggregate	0.4 in. (10 mm)
Calculated mixture design parameters	
Fine aggregate content	75.0%
Plastic density	140 lb/ft^3 (2240 kg/m^3)
Fly ash content (percent by mass of cement)	20.0%

added to produce an air content of about 4% for the hardened shotcrete.[6]

Sustainable Construction and Application

When applied to a receiving surface (for example, rock mass, soil, insulation board, plywood or steel formwork, or masonry for historical buildings), shotcrete is pneumatically projected at high velocity. This process provides good consolidation of the materials and minimizes the use of formwork. Compared to cast-in-place concrete construction, shotcrete typically reduces the amount and time for formwork installation, removal, and associated labor costs. For structural shotcrete, single-sided formwork can be used to provide a receiving surface (Fig. 1 and 2). For soil and rock slope stabilization projects when shooting against existing excavations (soil or rock), the use of formwork can often be eliminated entirely.

The modern dome construction process is another good example of using shotcrete with no formwork. An airform, which can also act as the final waterproofing membrane, is used as the form, with shotcrete applied from the inside (Fig. 3).

Fig. 1: Single-sided plywood formwork set up as a shotcrete receiving surface in California
Photo courtesy of Chris Zynda

Rebound Collection

Rebound is associated with the shotcrete application process. It can vary from 5 to 10% by mass of applied materials for wet-mix shotcrete, and 15 to 40% for dry-mix shotcrete. An appropriate collection of rebound materials and associated cuttings and trimmings from finished shotcrete surfaces can, however, reduce environmental impact. Rebound materials should not be reapplied to a shotcrete structure but can be collected (Fig. 4) and used as backfill materials for foundations or can be used to cast concrete blocks.

Shotcrete is Sustainable

The preceding review indicates that shotcrete, as currently used, is a green material and can be designed and applied in a sustainable way. Therefore, it is concluded that shotcrete is sustainable.

Having said that, it is important to ask the following questions:

- Have the construction and green-building industries recognized and accepted that shotcrete is sustainable?
- How does the sustainability of shotcrete help the development of the shotcrete industry?

Although numerous structures, including new construction and repair of buildings, bridges, dams, tunnels, retaining walls, swimming pools, and marine structures have been built or repaired with shotcrete for more than a century, there are still questions and concerns from owners, architects, and engineers regarding shotcrete and how it compares to cast-in-place concrete.[7] These can be summarized as follows:

- **Is shotcrete the same finished product as cast-in-place concrete?**
  Shotcrete is not yet recognized in all jurisdictions as a suitable construction technology when compared to conventional cast-in-place concrete construction. Questions are asked

Fig. 2: Shotcrete applied to a masonry wall for seismic retrofit for a heritage building in Vancouver, BC, Canada

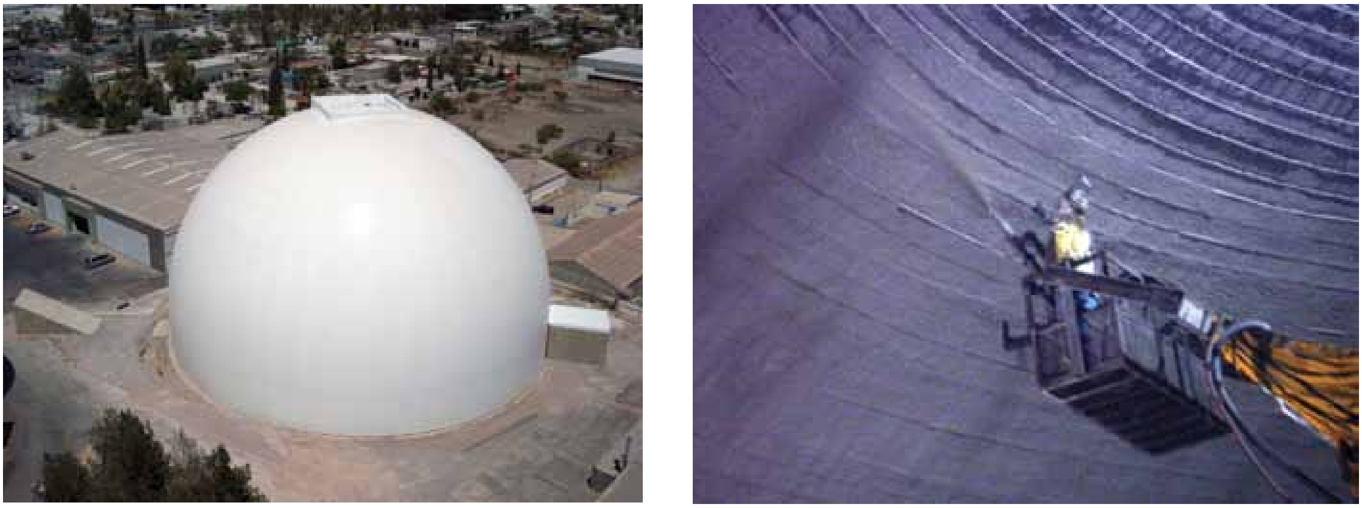

Fig. 3: Shotcrete applied to waterproof membrane to construct a dome
Photo courtesy of Ryan Poole

regarding the durability and permeability of shotcrete. Most of the time, previous project experience and the evaluation of mock-ups can be used to allay such concerns.

- **Is shotcrete durable?**
  Improvement of durability will extend the service life of the structure and therefore contribute to sustainability. Durability for shotcrete can be assessed by evaluating properties such as boiled absorption and volume of permeable voids (ASTM C642-06), resistance to freezing and thawing (ASTM C666/C666M-03(2008)), rapid chloride penetration (ASTM C1202-10), and others. Microstructure of the hardened shotcrete and fluid transportation mechanisms during the service life of the hardened shotcrete are important properties to understand in assessing durability. Some research work[8] found that the variation of cement paste content of the shotcrete, which is influenced by the gradation and percentage of aggregates in the mixture formulation, will affect permeability. There is still a need for more fundamental research, however, into the porosity, pore structures, and fluid transport mechanisms for shotcrete for durability to be more fully understood.

Making Shotcrete More Sustainable

Contribution to LEED Points

LEED certification is now frequently required for new buildings and it is important that shotcrete can be recognized to contribute to LEED points. LEED accepts technologies that can make buildings greener. Shotcrete can contribute to LEED points[9] with the use of SCMs. The following are specific methods:

- MR C4, one to two points, recycled content. Using 10% post-consumer and preconsumer waste, such as a fly ash as cement replacement, can garner one LEED point, and using 20% replacement can garner two LEED points.
- MR C8, one point, durable building. Using concrete to meet CSA durability requirements and life-cycle requirements. Construction of buildings with 100 years of design life will, for example, contribute to LEED points.
- MR C5, one to two points, regional materials. Using aggregate, cement, and SCMs produced and supplied locally will contribute to LEED points.

Fig. 4: Rebound materials collected and used as backfill materials

The reduction or elimination of formwork will reduce materials costs, shorten the construction schedule, and save labor costs. Time savings of up to 4 months in a 1-year construction schedule have been achieved. There is a large cost savings through the use of shotcrete instead of cast-in-place concrete for formwork setup and stripping and through the elimination of concrete vibration costs. The advantage of using shotcrete in terms of formwork cost savings is an important contribution to sustainability, but it has yet to be acknowledged by the green building industries. Unfortunately, the current LEED rating system has not yet recognized this advantage. It is up to the shotcrete industry to bring this important factor to the attention of the green building industry.

Here is a proposed LEED point system for considering the formwork savings with shotcrete:

total formwork used with form-and-pour construction
– total formwork used with shotcrete/total formwork used with form-and-pour construction
= LEED credit for formwork saving with shotcrete process

Note 1: The parameter to quantify formwork can be total cost, total quantities such as m^3 or m^2, or weight. It is recommended to use cost.

Note 2: Actual costs will vary for each project. For projects without a detailed breakdown of costs, however, an estimate could be made as outlined in Table 2.

The percentage cost savings to achieve a LEED credit needs to be determined by the shotcrete industry. For example, if a cost savings of 10% is set up to grant one LEED point, then the aforementioned example will contribute to one LEED point.

Formwork savings could contribute to the following potential LEED Credits Categories:

LEED New Construction Materials & Resources (MR)

- MR Credit 1 Building Reuse
- MR Credit 2 Construction Waste Management
- MR Credit 3 Resource Reuse
- MR Credit 4 Recycled Content
- MR Credit 5 Regional Content
- MR Credit 6 Rapidly Renewable Materials
- MR Credit 7 Certified Wood
- MR Credit 8 Durable Building

Repair and Rehabilitate with Shotcrete

The majority of aging concrete structures need to be repaired and rehabilitated across North America. Repair and rehabilitation are among the most effective ways to make structures sustainable. Repair of an existing structure will extend its service life of the structure as opposed to demolishing it and building an entirely new structure. Rehabilitation of existing buildings will reduce energy consumption and contribute to a sustainable environment. Repair will reduce costs of materials and labor, minimize waste materials produced by demolition of the old structure, and reduce environmental impact during demolition and the new construction period. Shotcrete has been found to be particularly cost effective in a variety of repair situations, including[10]:

- where formwork is impractical or can be reduced or eliminated;
- where access to the work area is difficult;
- where thin layers and/or variable thickness is required; and
- where normal casting techniques cannot be employed.

Shotcrete bonds well to the substrate concrete if the substrate is prepared properly, and this will result in extended service life for the structure, in particular for the structures that have deteriorated severely. Figure 5 shows an example of repair of a seawall with shotcrete.

Table 2: Example of formwork savings with structural shotcrete for a commercial building
(numbers are for demonstration purposes only)

Provide total formwork cost with form and pour (including labor, equipment, and materials)
Provide total formwork cost with shotcrete (including labor, equipment, and materials)

Structure component	Company	Form-and-pour cost, U.S.$			Shotcrete cost, U.S.$		
		Formwork materials costs	Labor costs	Equipment, including crane costs	Formwork costs	Labor costs	Equipment, including crane costs
Foundation walls	Shotcrete contractor	10,000	10,000	10,000	0	5000	0
Columns	Shotcrete contractor	10,000	10,000	10,000	10,000	10,000	10,000
Beams	Shotcrete contractor	10,000	10,000	10,000	10,000	10,000	10,000

Note 1: Formwork material costs include costs for wood or steel formwork; labor costs include costs for formwork erection, fasteners, removal, and costs to finish the structure; and equipment costs include crane costs.

Note 2: This is an example only; actual numbers can be calculated for an actual structural shotcrete project.

Total costs for form and pour: $90,000
Total costs for shotcrete: $75,000
Percentage of cost savings with shotcrete: 17%

Most green building rating systems, including LEED, have not yet included repair and rehabilitation as a factor to achieve a point for being sustainable. This allowance should be made, however, because repair and rehabilitation with shotcrete will improve the service life through enhancement of the durability of the existing buildings, and this will lead to the sustainability of structures and buildings.

Seismic Retrofit with Shotcrete to Extend Service Life and Sustainability

More and more buildings and structures are getting close to their design service life as the inventory of buildings needing seismic retrofitting increases. Retrofitting of existing structures and building improves the durability and therefore extends service life. In particular, the seismic retrofit of existing buildings and structures strengthens the structure to meet updated building standards for earthquake requirements. Across North America, many historical buildings are required to be preserved. Figure 6, for example, shows a historical masonry building that was built in 1912 and was seismically retrofitted in 2008 with structural shotcrete.[11] Reinforced shotcrete walls and pilasters were constructed inside of the masonry façade shown in Fig. 6. The historical exterior masonry façade remained for decorative purposes. Retrofitting historical buildings preserves the culture and heritage of the community and therefore contributes to sustainable development.

Retrofit of existing buildings also reduces energy consumption. According to Morgan and Zhang,[12] retrofit of existing buildings in Switzerland could reduce the total national energy consumption by 25% and greenhouse gas emission by 50%. The energy consumption of buildings retrofitted with shotcrete has not typically been calculated. The merits of using shotcrete for retrofitting needs to be studied and assessment measures need to be established.

Other Areas that Shotcrete Might Contribute to LEED Points

Using shotcrete, especially structural shotcrete for buildings, has advantages in thermal transmission. This is related to LEED Energy & Atmosphere C1, 1-10 points, and optimized energy performance. Using concrete to reduce thermal energy consumption, this can be achieved by energy modeling.[13] This includes applying shotcrete to insulated panels to provide a good balance of thermal mass and insulation in the proper locations.

Fig. 5: Shotcrete repairs to damaged concrete faces rip-rap in the Devonian Park part of the Stanley Park Seawall in Vancouver, BC, Canada
Photo courtesy of D.R. Morgan

Fig. 6: Seismic retrofit of the 100-year-old Wing Sang Building in Vancouver, BC, Canada

Conclusions

Shotcrete is a sustainable material and can be applied by a sustainable method to construct durable structures. The shotcrete industry has been applying shotcrete in a sustainable way by the integration of advanced green technologies since its inception a century ago. Recognition and acceptance of sustainable shotcrete is needed in the shotcrete industry, the construction industry and, most importantly, the green building industry. This article is intended to open a window for the discussion and reevaluation of shotcrete from the aspect of sustainability.

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