# A REVIEW REGARDING THE SUSTAINABLE USE OF SHOTCRETE AT NATIONAL AND INTERNATIONAL LEVEL

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**ABSTRACT**

The process of application of concrete and mortar by shotcrete was invented in the US at the beginning of the 20th century. In 1907, the American Carl Akeley used this method to repair the facade of the Columbian Museum in Chicago (the old Palace of Fine Arts of the World's Columbian Exhibition). In 1911, Carl Akeley received a patent for the "cement gun". At present, the shotcrete is used both for new construction and repair / rehabilitation of old buildings. The aim of this study was to present, analyse and synthesise the current references existing in the literature, presenting the two currently used methods for obtaining shotcrete: dry and wet.

*Keywords*: shotcrete; state-of-the-art; sustainability.

**REZUMAT**

Procesul de aplicare a betonului și mortarului de beton prin torcretare, a fost inventat în SUA la începutul secolului al XX-lea. În 1907, americanul Carl Akeley a folosit această metodă pentru a repara fațada Muzeului Columbian din Chicago (vechiul Palat al Artelor Frumoase din expoziția columbiană a lumii). În 1911, Carl Akeley a primit un brevet pentru "pistolul de ciment". În prezent, betonul torcretat este utilizat atât pentru construcții noi, cât și pentru repararea sau reabilitarea clădirilor vechi. Scopul acestei lucrări este de a prezenta, analiza și sintetiza referințele existente în literatura de specialitate, prezentând cele două metode existente de realizare a betonului torcretat: uscat și umed.

*Cuvinte cheie*: beton torcretat; stadiul actual; sustenabilitate.

## 1. INTRODUCTION

The process of application of concrete and mortar by using shotcrete, was invented in the US at the beginning of the 20th century. In 1907, American Carl Akeley used this method to repair the facade of the Colombian Museum in Chicago (the Old Palace of Fine Arts of the Colombian World Exhibition). In 1911 Carl Akeley received a patent for the "cement gun". The shotcrete machine later appeared in 1950 (Yoggy, 2002).

According to the American Concrete Institute, shotcrete is defined as "mortar or concrete pumped pneumatically, at a high speed on a certain surface" (Hanskat, 2010).

The application of shotcrete can only be done with special equipment consisting from: a machine or a pump in which the mixture is introduced; transportation pipe or hose, through which the concrete is brought to the application site and a nozzle, fixed at the end of the pipe or hose.

At present, shotcrete is used for both new constructions as well as in the repair or rehabilitation of old buildings (Morgan, 2006).

Sustainability is, in general, the sum of concepts and behaviors "that meet the needs of the present, without compromising the ability of future generations to meet their own needs" (Fix and Richman, 2009).

The advantages of the shotcrete are the durability; the possibility of making complex concrete forms with a low degree of use of the moulds; increasing building speed by 30-50%; reducing the workforce by approximately 50% in repairs; reducing the degree of use or disposal of cranes and other equipment. As a result of the increased speed of repairs, the interruption times in the operation of the structure are reduced; adaptability to repair surfaces for which other processes are not profitable; the possibility of being carried out in a restricted area and in hard-to-reach areas, including underground, and the use of a wide range of recycled materials (glass, rubber, ash, etc.) for this type of concrete. All this demonstrates the sustainability of shotcrete (Hankskat, 2010).

The aim of this paper is to present a synthesis of the current state-of-the-art literature regarding worldwide production, use and performance of shotcrete. The research methodology consisted in the study, analysis and synthesis of the references existing in the current literature.

## 2. USE OF SHOTCRETE – A REVIEW

### *2.1. Methods of producing shotcrete*

At present, there are two methods of producing shotcrete: wet and dry (Litvin and Shidler, 1966).

The method of applying of the mixture by the dry chewing process consists in, that the mixture made of aggregates having natural moisture, and cement are put together into the shotcrete machine and then transported by compressed air to the nozzle where the water dosing is then injected. The main characteristics of the dry method according to the literature are: the high speed of the shotcrete design of approximately 80-100 m / s and the possibility of vertical (up to approximately 150 m) and horizontal transportation over long distances (up to 500 m).

The wetting process consists in mixing of the cement, aggregates, water and any additives added to the shotcrete machine, from where it is sent via pipe / hose pumping to the nozzle where the compressed air required for the desired design is introduced.

These shotcrete application technologies are used in various constructions and exceptional architectural achievements, such as buildings with irregular shapes, difficult to make using traditional methods, tunnels, mine galleries, foundations, slope stabilization, large channels, silos, swimming pools, etc. (Chrom, 1981). From research conducted over the years, it has been noticed that in Central Europe, mainly in Germany and Austria, the dry method of making shotcrete is preferred, whereas in Northern Europe, mainly in Norway and Sweden, the method is more popular (Beaupré, 1994).

The difference between the two methods is the water/cement ratio, which is much higher for the wet one, resulting in greater porosity and permeability, but also low resistance compared to the dry method (Warnerm, 1995).

### *2.2. Raw materials used in the production of shotcrete*

According to the literature, in the US, the amount of cement used in the preparation of shotcrete is 400-450 kg/m3 with a water/cement ratio of 0.50 to 0.35 and 600-1000 kg/$m^3$ of aggregates of different sorts (Beaupré, 1994).

Regarding aggregates, research has shown that three types of natural limestone can be used as sand (0-4 mm), coarse aggregate (4-6 mm) and (6-8 mm) in the following percentages: 65:30: 5 (Zaffaroni et al., 2001).

The most used admixtures are water reducers, air coaches, superplasticizers and outlet accelerators. The latter are mainly used because it accelerates the hydration of tricalcium aluminate, $C_3A$, contributing intensely to the formation of the interstitial gel, respectively improving the rheology of the fresh concrete (Beaupré, 1994; Haave and Bracher, 1993). There are two types of accelerators used for traditional shotcrete, based on a solution of sodium silicate (36%) and a non-alkaline one based aluminum sulphate emulsion (60%). Due to the absence of alkalis, there is a low risk of causticity during application (Zaffaroni et al., 2001).

Literature presents the results of experimental research in which a 30% aqueous solution of carbo-acrylic ester was used as a superplasticizer to produce fluid concrete with a 210÷220 mm range with a water/cement ratio of 0,42-0,44 (Zaffaroni et al., 2001).

Fly ash was also used in wetted shotcrete, starting in the 1970s in Norway, and since the 1980s it has been used in Canada for blending with different types of fibers (Zaffaroni et al., 2001).

From the analysis of the work done over time, there are references to new materials used in the manufacture of shotcrete, such as glass dust, recycled plastics, fibers (metallic and polypropylene) of various shapes and sizes and recycled rubber granules from used tires (Gagnon et al., 2016).

In the world, only 30% of the total glass is recycled. Grinding the glass and turning it into powder is a way to create a new ingredient for the shotcrete that has been sprayed, offering the possibility of introducing glass waste into the concept of circular economy (Fily-Paré and Jolin, 2013). Glass powder, resulting from its milling, can be used in the dry method. Experimental research has shown that for concrete to be sprayed, approx. 20% glass powder and 10% fly ash from the total amount of cement can be replaced (Gagnon et al., 2016).

Lately, other wastes have been used in dry mixes for shotcrete, but in this case as a replacement for natural aggregates - PVC aggregates, crushed into small particles. Generally, PVC waste can be recycled in an efficient way, but the category of waste that can't be properly sorted for traditional recycling by crushing to controlled granulation, can be introduced as a material in shotcrete.

Large quantities of tires are consumed annually, for which there are many ways to recycle and reuse. Therefore, the rubber powders have become available in large quantities and are particularly inexpensive, becoming a material of interest by capitalizing on the making of shotcrete.

Both categories of alternative aggregates (PVC and rubber aggregates) have shown to induce workability problems for cast concrete. The most appropriate method of using these products has been the dry-mixing process of the shotcrete. Experimental research in which alternative aggregates replaced 20% of total aggregate volume as a sand substitute has demonstrated, as expected, a reduction in mechanical strength due to the poor mechanical properties of these types of recycled aggregates (Gagnon et al., 2016). However, the quality of the concrete could be good enough in many applications due to the high replacement rate used and the possible optimization of the mixes.

Due to low rigidity, alternative aggregates may also have areas of use, as they have high deformability and high energy absorption (Gagnon et al., 2016).

### *2.3. Performance of shotcrete*

#### *2.3.1. Fresh shotcrete*

The main properties of interest of fresh shotcrete are: pumpability, compactibility, design speed, mobility, and stability.

In order to achieve a good quality, the concrete must have the proper compacting and finishing properties.

Because each application, depending on the use, is different (floor finishing, fluid concrete, self-compacting concrete, pumped concrete, concrete, etc.), each type of shotcrete requires its own conditions of workability, transportation, fluidity, compaction and finishing. Shotcrete must be designed in such a way that any minor change in the dosage of the component materials does not substantially affect the properties of the fresh and hardened state. The concept of stability is very important; the properties of the fresh shotcrete need to be maintained during the entire duration of the spraying, finishing, etc.

The workability refers to the correlation between the component materials and the fulfillment of all the conditions imposed by each application (Beaupré, 1992).

Physical properties are determined by tests that are based on parameters such as viscosity, cohesion, internal friction, pumpability, stability, segregation, compactibility, etc.

Pumping is defined as the mobility and stability of pressurized concrete in a closed hose, in other words, pumpability is pressurized mobility (Beaupré, 1992).

By stability, the ability of the concrete to maintain its initial homogeneity during transport, handling or placement is defined.

Compactibility refers to the ease with which the concrete is fully compacted. For fluid concrete, the required energy is obtained by vibration. For shotcrete, the particle velocity that depends on the amount of compressed air used in the nozzle and its impact on the design surface creates a compaction effect (Beaupré, 1992).

### *2.3.2. Hardened shotcrete*

The following tests can be carried out on hardened shotcrete: compressive strength, tensile strength, elastic modulus determination, tear strength determination, permeability, fiber content determination and freeze-thaw resistance (EFNARC, 1996).

Several values certified by national Technical Approvals on determinations made on hardened shotcrete, taken in the laboratory are shown in Table 1, and those obtained in-situ in Table 2.

**Table 1.** Laboratory physical and mechanical characteristics of shotcrete

| Characteristic | 0/2 mm sieve C25/30 | | 0/4 mm sieve C16/20 | | 0/4 mm sieve C25/30 | | 0/4 mm sieve C35/45 | |
|---|---|---|---|---|---|---|---|---|
| Apparent density of hardened mortar (kg/m$^3$) | 2040 | | 2100 | | 2040 | | 2150 | |
| Tensile strength (N/mm$^2$) | Age (days) | $R_{ti}$ | Age (days) | $R_{ti}$ | Age (days) | $R_{ti}$ | Age (days) | $R_{ti}$ |
| | 28 | 4,7 | 28 | 5,5 | 28 | 4,9 | 28 | 5,5 |
| Compressive strength (cubes) (N/mm$^2$) | Age (days) | $R_c$ | Age (days) | $R_c$ | Age (days) | $R_c$ | Age (days) | $R_c$ |
| | 28 | 30,8 | 28 | 21,3 | 28 | 31,1 | 28 | 45,9 |
| Water absorption – capillarity absorption / kg (m$^2$min$^{0,5}$) | 0,5 | | 0,5 | | 0,5 | | 0,3 | |
| Support adhesion (N/mm$^2$) | Con-crete support | 3,0 | - | - | - | - | - | - |
| | Mode | Cohe-sive | - | - | - | - | - | - |

**Table 2.** In-situ physical and mechanical characteristics of shotcrete

| Characteristic | 0/4 mm sieve C25/30 | 0/8 mm sieve C25/30 |
|---|---|---|
| Compressive strength (cilinders) (N/mm$^2$) | 35,9 | 29,8 |
| Support adhesion - resistance (N/mm$^2$) | Rock support | >1,55 |
| | Mode | Cohezive |

As seen in Table 1, compressive strengths of up to 45.9 N/mm$^2$ have been obtained on the shotcrete in laboratory conditions, depending on the grade shotcrete class, given in accordance with those reported in the literature (Beaupré, 1992).

For mining galleries and tunnels, where the rock has a low stability due to cracks, a very high resistance shotcrete must be obtained in a short time. Thus, according to Reny and Clement, the following results were obtained in the laboratory, on shotcrete, which was sprayed with calcium sulfo-aluminate sink accelerators and cements (Reny and Clements, 2013), shown in Figure 1 and Figure 2.

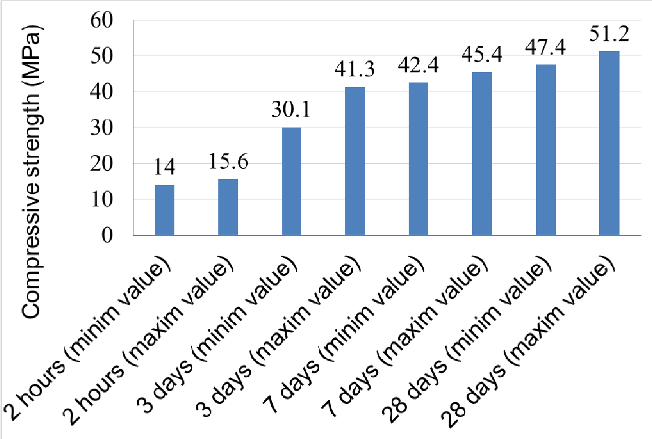


**Fig. 1.** Compressive strength (MPa) of shotcrete used for mining galleries ranging from 2 hours to 28 days (Reny and Clements, 2013)

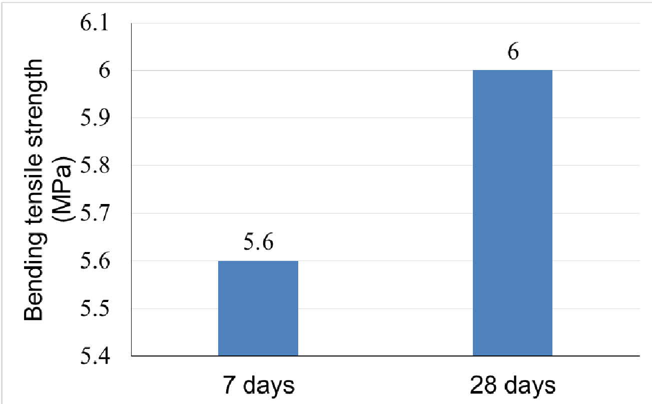


**Fig. 2.** Bending tensile strength (MPa) of shotcrete used for mining galleries (Reny and Clements, 2013)

### *2.3.3. Use of shotcrete for new construction and rehabilitation of old buildings*

Shotcrete can be used both in new construction and in the rehabilitation of old ones, as exemplified in Figure 3 and Figure 4.

**Fig. 3.a.** The Greek-Catholic Cathedral in Cluj-Napoca, with a height of 48 m, to which the shotcrete was sprayed over the brick masonry (Radio Cluj, 2019)

**Fig. 3.b.** VanDusen Botanical Garden, Canada (Hawkings, 2013)

**Fig. 3.c.** History Museum of the Polish Jews in Warsaw, built in 2012, with a wall height of 26 m and an area of approx. 6000 m$^2$ (Czajka, 2013)

**Fig. 3.** Use of shotcrete for new buildings

**Fig. 4.a.** Targeting the walls of an anchor excavation and protecting it with shotcrete. Palace of Justice in Iasi (PROXEROM, 2019)

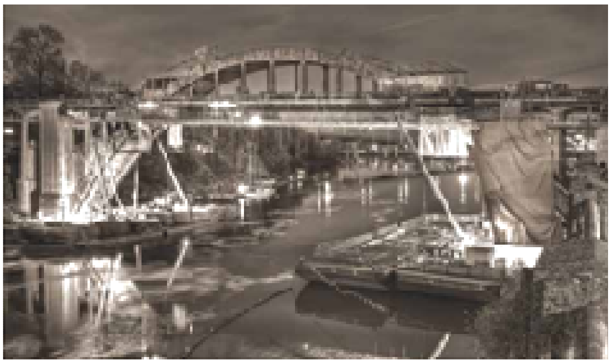

**Fig. 4.b.** The Oregon Bridge over the Willamette River, rehabilitated in 2012 (Marcus, 2014)

**Fig. 4.c.** Blaine Hill Viaduct 40 Ohio (US) built in 1933, with a 307m (307m) length of concrete (Pinney, 2012)

**Fig. 4.** Use of shotcrete for rehabilitation of old structures

### *2.4. Normative documents*

The following European standards are currently used at national and EU level: SR EN 1504 series (ASRO, 2006a) relating to products and systems for the protection and repair of concrete structures and series SR EN 14487 (ASRO 2006b) and SR EN 14488 (ASRO, 2005) with regard to shotcrete, as well as technical instructions for the application of shotcrete.

## 3. CONCLUSIONS

Based on the literature, it can be concluded that:

- at present, there are two ways of producing shotcrete: dry and wet.
- the dry application technology consists in that the mixture made of cement and aggregates at natural humidity is introduced into the machine and then conveyed by compressed air to the nozzle where the amount of metered water is injected. The main advantages of this method are the high speed of concrete

design (approximately 80-100 m/s) and the possibility of vertical transport up to approximately 150 m and horizontally over long distances up to 500 m.
- the dry application technology generally uses cements with or without admixtures for the preparation of mixtures for shotcrete. The wet application technology consists in the fact that the mixture with water is carried out in the spraying machine from where it is sent by pumping into the duct/hose to the nozzle where the compressed air required for the design is introduced. The advantages of this torque method are: less concrete design speed (about 10-40 m/s); the possibility of designing a large flow of concrete; the possibility of using additives.
- the main factors contributing to the good quality of the concrete are: the compressed air flow; water / cement ratio.

Shotcrete with very good properties can be obtained with both classical materials and recycled materials. Both high-strength, low permeability and high durability can be achieved by both wet and torque processes. In order to obtain the best results, it is possible to introduce socket accelerators or different types of fibers and additives. However, in order to achieve a high performance shotcrete, not only an optimal mix design is sufficient, but also a close link between all the properties of the final material.

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