Revista EIA

# Shotcrete: Historical and Technical Overview



Revista EIA
ISSN 1794-1237
e-ISSN 2463-0950
Año XIX/ Volumen 22/ Edición N.44
Julio - diciembre 2025
Reia4421 pp. 1-26

Publicación científica semestral
Universidad EIA, Envigado, Colombia

**Para citar este artículo / To reference this article /**
Berrio-Alzate, A.; Aguirre-Giraldo, I.; Ramírez-Suarez, L. Y. y Alvarez-Montoya, A.
Shotcrete: Historical and Technical Overview

Revista EIA, 22(44), Reia4421 pp. 1-26
https://doi.org/10.24050/reia.v22i43.1883

*Autor de correspondencia:*
Berrio-Alzate, A
Maestria en ingenieria
Correo electrónico:
aberrioa@unal.edu.co

**Recibido:** 01-04-2025
**Aceptado:**10-06-2025
**Disponible online:** 01-07-2025

Andres Berrio-Alzate, M.Sc.[1]
Isabela Aguirre-Giraldo[1]
Leidy Yohana Ramírez-Suarez[1]
Andrea Alvarez-Montoya, C.E.[2]

1. Universidad Nacional de Colombia, Sede Medellín
2. Construcciones El Condor S.A.

## Abstract

Shotcrete is one of the most significant innovations in the construction industry. What began as an experimental technique has evolved into essential technology, valued for its versatility and efficiency in projects ranging from structural repair and stabilization to the construction of tunnels, mines, open-pit excavation linings, and dams. Its ability to be sprayed at high speed onto various surfaces—even under complex conditions—combined with its rapid hardening process sets it apart from conventional concrete placement methods.

The history of shotcrete is defined by key milestones in its development, from the introduction of dry application techniques to the later innovation of the wet process, which greatly enhanced the material's quality, consistency, and efficiency. These advancements have been accompanied by progress in materials science and technology, optimizing shotcrete's mechanical properties and durability. Additionally, continuous improvements in application equipment have transformed it from rudimentary manual systems to high-precision automated technologies.

This historical overview not only highlights the technical evolution of shotcrete but also underscores its impact on modern construction methodologies. This review explores the most significant moments in its development, along with the progressive and incremental innovations that have solidified its status as a fundamental tool in engineering projects and the construction of complex infrastructure worldwide.

***Keywords:*** shotcrete; material technology; infrastructure; wet-mix; dry-mix; robot jet; additives; standardization; regulations; construction.

# Concreto Lanzado: Revisión Técnica e Histórica

## Resumen

El concreto lanzado, representa una de las innovaciones más significativas en la industria de la construcción. Desde sus inicios como una técnica experimental, ha evolucionado hasta convertirse en una tecnología esencial, cuya versatilidad y eficiencia la han hecho indispensable en proyectos que van desde la reparación y estabilización estructural hasta la construcción de túneles, minas y revestimientos de excavaciones a cielo abierto y presas. Su capacidad para ser proyectado a alta velocidad sobre diversas superficies, incluso en condiciones complejas, junto con su rápido endurecimiento, lo diferencia de los métodos convencionales de colocación de concreto.

La historia del concreto lanzado está marcada por hitos clave en su desarrollo, desde la introducción de las técnicas de aplicación por vía seca, hasta la posterior innovación de la vía húmeda, que mejoró significativamente la calidad, la consistencia y la eficiencia del material. Este progreso ha estado acompañado de avances en la ciencia y tecnología de los materiales, que han permitido optimizar sus propiedades mecánicas y de durabilidad, así como de mejoras constantes en los equipos utilizados, que se han transformado desde sistemas manuales rudimentarios, hasta tecnologías automatizadas de alta precisión.

El recorrido histórico que se presenta en este artículo, no solo destaca la evolución técnica del concreto lanzado, sino también su impacto en las metodologías de construcción moderna. En esta revisión, se exploraron los momentos más relevantes de su desarrollo, así como las innovaciones progresivas e incrementales, que le confirieron su lugar como una herramienta fundamental para los proyectos de ingeniería y el desarrollo de infraestructuras complejas alrededor del mundo.

***Palabras clave:*** concreto lanzado; tecnología de materiales; infraestructura; mezcla húmeda; mezcla seca; robot jet; aditivos; estandarización; normativa; construcción.

## 1. Introduction

Shotcrete has undergone a remarkable evolution since its invention by Carl Akeley in 1907. Initially conceived as an ingenious method for applying mortar at high speed to various surfaces, it was soon implemented in landmark projects such as the restoration of Chicago's Columbian Museum and the construction of the Panama Canal. These early applications marked a turning point in its adoption within the construction industry.

The evolution of shotcrete has been driven by continuous advancements in machinery, materials, and application techniques. One of the most significant breakthroughs was the transition from the dry process to the wet process, which enhanced the material's workability and optimized the spraying method. Additionally, the incorporation of fibers, additives, and innovative materials has significantly improved its durability and strength, enabling its use in a broader range of infrastructure applications.

Since the 1950s, advancements in equipment have optimized the shotcrete application process. In the 1970s and 1980s, the standardization and regulation of its practices by various international institutions further cemented its reputation as a reliable and efficient technique. Today, the integration of quality control processes and continuous innovation in shotcrete components have enabled it to achieve exceptional performance in modern construction.

This paper provides a historical and technical review of shotcrete, tracing its evolution from its origins to the present day. It highlights key advancements in machinery, materials, and regulations while examining their effects on optimizing shotcrete performance. Additionally, the paper presents findings from recent studies that demonstrate its impact on the construction industry. Emerging trends aimed at enhancing this technique and adapting it to the evolving demands of the sector are also analyzed.

## 2. Methodology

This study presents a historical and technical review of shotcrete, tracing its evolution from its origins to the present. It analyzes advancements in machinery, materials, and regulations to evaluate their impact on the construction industry. The research is based on a comprehensive compilation and analysis of scientific literature, technical regulations, and institutional documents related to shotcrete. Data was gathered from specialized databases such as Scopus, Web of Science, Google

Scholar, and institutional repositories. Articles, standards, and manuals published between 1950 and 2024 were selected, with priority given to peer-reviewed publications recognized by the scientific community.

The inclusion criteria encompass academic publications and regulations pertaining to shotcrete, investigations into advancements in materials, equipment, and specifications, as well as technical documents containing performance data and applications. Reports lacking scientific support, outdated or irrelevant publications, and studies exhibiting substantial methodological bias were excluded.

The findings are influenced by the availability and quality of published information. Additionally, variability in reporting criteria may have impacted the comparability of certain results. The references include international technical standards, scientific articles, and manuals from specialized institutes, with a comprehensive list provided at the end of the document.

## 3. Development

### *3.1. Early 19th century*

Carl E. Akeley—taxidermist, sculptor, biologist, and inventor—worked at Chicago's Columbian Museum (now the Museum of Science and Industry) alongside Clarence Dewey, who was responsible for painting landscapes for the museum's exhibits. To assist with this task, Dewey used a machine invented by Akeley that utilized compressed air to spray colored plaster. Recognizing its potential, the museum's director, Frederick Skiff, suggested that Akeley design a similar but larger-scale machine to restore the building's deteriorating façade (Bridger, 2017).


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***Figure 1.*** *Carl Akeley at the Field Museum of Natural History in Chicago (Bridger, 2017).*

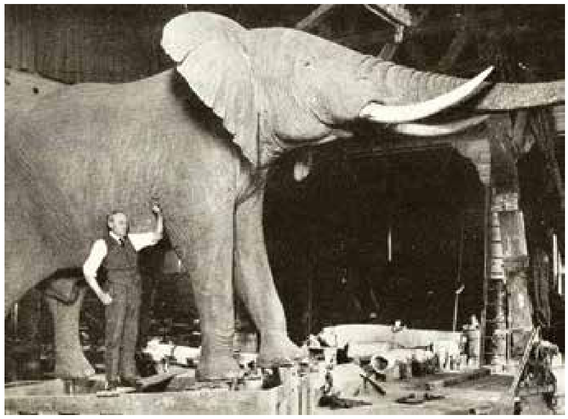
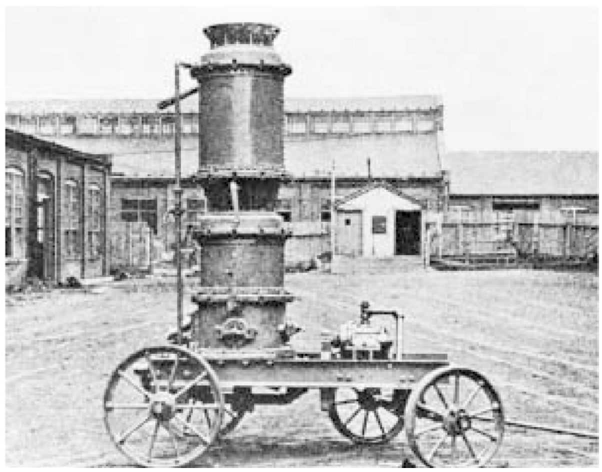


***Figure 2.*** *Original double-chamber cannon developed by Carl Akeley in 1907 (Morgan & Bernard, 2017).*



Teichert (2002) explains that, in June 1907, Akeley introduced the first version of the Plastergun, a rudimentary machine based on a double-chamber principle. The material was transported through a hose from two vertically aligned chambers, which were alternately pressurized. Upon reaching the nozzle, water was added to moisten the material before it was pneumatically projected onto the surface. This innovation laid the foundation for what is now known as the double-chamber gun.

Between 1908 and 1909, Carl E. Akeley continued adapting the Plastergun for use with other materials, such as Portland cement and sand mixtures. In 1909, he applied for a patent for his invention, which was granted in May 1911 under the name “Apparatus for Mixing and Applying Plastic or Adhesive Materials.” Dufour and Jolin (2010) mention, prior to that, in December 1910, he had showcased his invention, now called the Cement Gun, at the Madison Square Garden Cement Show, where it achieved immediate success due to its groundbreaking ability to apply mortar to surfaces at high speed.

The first practical results of the Plastergun were showcased at the Seventh Annual Convention of the National Cement Consumers Association, where its effectiveness was demonstrated in the lining of the Hunter Brook Siphon in Yorktown. Yoggy (2005) notes that other notable projects included the lining of structural elements at New York’s Grand Central Station and the stabilization of rock slopes during the construction of the Panama Canal by the United States Army Corps of Engineers.

In 1912, civil engineer Samuel Taylor acquired the rights to the machine and registered for the Gunite trademark. The original model, known as the Model GL, remained unchanged, preserving all of Akeley’s original design features. However, in 1914, Model N-0 was introduced, featuring modifications to the vessel geometry. This was followed by Model N-2 in 1916, which improved both ergonomics and application precision (Bridger, 2017)

Thanks to its exceptional durability, shotcrete became a highly versatile technique with a wide range of applications. Dudley and Jolin (2022) state that it was extensively used in building repair and construction, culvert and tunnel lining, rock slope stabilization, ground support in mines, and the repair of bridges, dams, and canals. Additionally, it played a crucial role in corrosion and fire protection for steel structures and the construction of water-retaining structures.

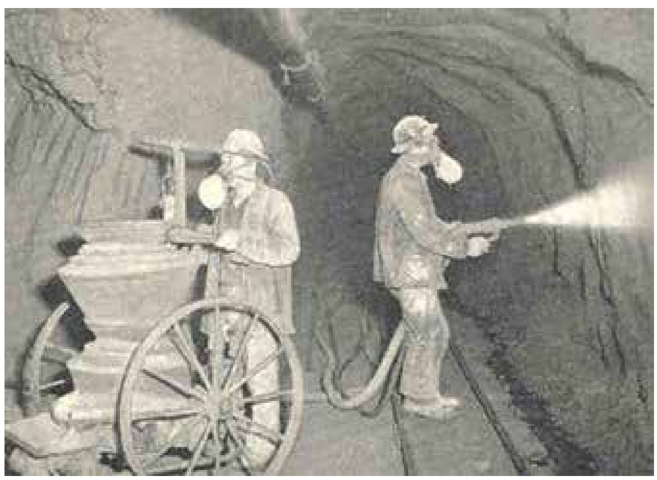
According to Dudley and Jolin (2022), the first investigations into the properties of gunite were conducted in 1917 by Professor M.O. Fuller at Lehigh University in Pennsylvania. The University of California later expanded these studies by quantifying the material’s physical properties and characterizing its compressive strength, density, and watertightness. The latter property proved especially relevant for the construction of structures designed to retain and/or transport water, consolidating the use of gunite in these types of applications.

### *3.2. 1920s, 1930s and 1940s*

By 1920, the Cement Gun Company had established itself as a leading contracting organization, promoting the use of Gunite across North America. Morgan and Bernard (2017) highlight that this expansion facilitated its globalization, reaching Germany in 1921, the United Kingdom in 1924, and, by the late 1920s, spreading to Europe, India, and South Africa.

During this period, until 1940, the double-chamber gun remained the dominant method for material application, with the company holding a monopoly on its production and use. A notable example of its effectiveness was the construction of the Willamette River Bridge in Oregon in 1922, which showcased the equipment's speed and efficiency in large-scale projects.

***Figure 3.*** *Lining a tunnel with gunite using a double-chambered barrel in the 1920s (Morgan & Bernard, 2017).*



Pye (2006) mentions that, in the early 1930s, the American Railway Engineering Association (AREA) introduced the term Shotcrete to standardize the designation of the dry-mix shotcrete process, unifying terminology used by various companies worldwide, such as Gunite, Jetcrete, Guncrete, and Spraycrete.

According to Austin (1999), by 1936, organizations like American Society for Testing and Materials (ASTM) and American Concrete Institute (ACI) began developing technical specifications related to materials, testing methods, concrete design, and construction practices. Additionally, before 1939, further research was conducted at various institutions, including the University of Toronto, the United States Department of the Navy, and the American National Standards Institute (ANSI).

Dudley and Jolin (2022) explain that the 1933 Long Beach earthquake in California marked a significant milestone in the use of shotcrete, as it played a crucial role in seismic retrofitting and the rehabilitation of buildings, including hospitals and schools in the affected areas.

In 1942, ACI Committee 805, specializing in pneumatically applied mortar, drafted ACI 805-51, titled "Recommended Practice for the Application of Mortars by Pneumatic Pressure." This document officially adopted the term Shotcrete, replacing previous designations such as "pneumatically placed mortar." (Austin, 1999).

### *3.3. 1950s*

After World War II, the world experienced significant transformations in culture, economy, society, and lifestyles, which drove changes in the techniques, equipment, and materials used in shotcrete.

Hay (2017) notes that one of the most significant advancements of the decade was the development of the wet-mix process, driven by the need for more efficient industrial applications compared to dry mixing. This innovation aimed to address the environmental drawbacks of dry mixing, such as dust generation, high material losses, and limited dosage control.

In 1951, the ACI proposed standardizing the term Shotcrete to refer exclusively to the dry-mix process. However, with the introduction of the wet-mix process, a new classification was established: Dry-mix Shotcrete for the dry process and Wet-mix Shotcrete for the wet process. Due to the ACI's normative influence, this terminology was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widely adopted in the United States, Canada, and other countries referencing ACI standards, while in Europe and other regions, the predominant term remained Sprayed Concrete (Pye, 2006).

In 1957, the former ACI Committee 805 was reactivated as Committee 506, with an expanded focus to include shotcrete. According to Balck (2016), this committee took on the responsibility of reviewing and updating recommendations for its application, becoming the primary authority on standards and technical guidance in the years that followed.

This decade also saw significant advancements in application equipment, driven by post-World War II technological progress. Yoggy (2005) mentions that, in Michigan, NFS Industries developed the Jetcreter, the first rotary barrel machine. This innovative design allowed material to descend by gravity from the hopper into the rotor cavities, which then rotated to align with the outlet tube. At this point, compressed air propelled the material forward, with an additional air injection at the outlet neck to generate the necessary volume and pressure for concrete expulsion.

Following this breakthrough, various types of rotary barrel guns were developed in other cities across the United States and Europe, further advancing shotcrete application technology.

The Jetcreter achieved great success, and in 1957, Hans Egger introduced the Meyco GM-57, an improved, more compact machine that became one of the most widely used in tunnel construction due to its efficiency and size. A smaller version, the Meyco GM-27, was later developed, while the Aliva brand entered international markets with its own variant of the rotary-barrel gun (Yoggy, 2005).

***Figure 4.*** *Meyco GM 57 rotary barrel pistol (Teichert, 2002).*

Another notable advancement, emphasized by Yoggy (2005), was the Micon Rig, designed by Jack Ridley, which featured a dual tank mixing and feeding system mounted on a trailer. These innovations significantly increased productivity, reduced labor requirements, and enabled the use of coarse aggregates (up to 10 mm) in the batching process, making the dry mix more comparable to conventional concrete.

***Figure 5.*** *MiCon Rig, presented by Jack Ridley (Yoggy, 2005*



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Hay (2017) states that the first wet-mix shotcrete applications were carried out using conventional pumps, though these proved inefficient for the task. As a result, several manufacturers focused on developing rotary guns with continuous feed systems, which significantly enhanced productivity and efficiency in shotcrete application.

Dudley and Jolin (2022) mention that during this decade, admixtures began playing a crucial role in shotcrete proportioning. Initially, air-entraining admixtures were used in wet mixes to enhance freeze-thaw durability. Later, water-reducing admixtures were introduced to decrease water demand in wet mixes, while setting accelerators were incorporated into dry mixes to speed up the setting process. These accelerators, typically composed of sodium or potassium aluminate, were highly alkaline improving setting time but potentially compromising the permeability and durability of the concrete.

### *3.4. 1960s*

In the early 1960s, Frank Reed developed innovative shotcrete equipment based on a rotating plate system. In this design, material descended by gravity from the hopper into U-shaped rotor cavities. Once the outlet neck aligned with the cavities, compressed air was injected to propel the material through the hose. Although this design proved successful, its rapid adoption—combined with the ease of operation and lack of process controlled to a decline in industry standards, ultimately impacting both the credibility of the method and the quality of the final product (Yoggy, 2005).

For over four decades, shotcrete has been recognized as one of the most successful construction technologies worldwide. However, this period of decline underscored the need to enhance training, education, best practices, research, and communication to ensure more efficient processes and high-quality results (Dufour & Jolin, 2022).

In response to these challenges, Joseph J. Shideler and Albert Litvin, researchers at the Portland Cement Association (PCA) Research and Development Laboratory, played a pivotal role in the revitalization of shotcrete. These experts published an extensive range of articles covering both wet-mix and dry-mix shotcrete processes.

Their studies explored key aspects such as mix design, application techniques, finishing, curing, and shotcrete properties. Additionally, they conducted comparisons of different equipment and assessed the quality of the final product, providing a solid foundation for the standardization and continuous improvement of this technology (Dudley & Jolin, 2022).

### *3.5. 1970s*

In the early 1970s, shotcrete production in North America was composed of 75% dry mix and 25% wet mix, with traditional methods from previous decades still prevailing. This context led research and technological development to remain primarily focused on the dry-mix process (Yoggy, 2005).

In this context, Dudley and Jolin (2022) note that one of the most significant advancements during this period was the introduction of steel fiber-reinforced shotcrete (SFRS) as a form of structural reinforcement. The first experimental studies on this technology were conducted in 1971 by D.R. Lankard and Parker at the Battelle Memorial Institute.

The first practical application of SFRS occurred in 1972, when the United States Army Corps of Engineers used this technology to stabilize bedrock and line a tunnel in the Ririe Dam in Idaho (Dudley & Jolin, 2022). Similarly, in Canada, the first use of SFRS took place in 1976 during a railway embankment stabilization project in Burnaby.

Meanwhile, in Norway, condensed silica fume was introduced for the first time as a supplementary pozzolan in shotcrete mixes, marking a significant milestone in enhancing the material's mechanical properties and durability (Dudley & Jolin, 2022).

In the regulatory arena, the United States made significant progress through the work of Committee 506 of ACI, which by this decade had already developed a series of technical guides aimed at standardizing shotcrete application processes.

In contrast, Europe experienced a slower regulatory progression, with the first regulatory codes emerging around 1976, developed by institutions such as the Association of Gunite Contractors and the Concrete Society (Pye, 2006).

By the late 1970s, Hay (2017) mentions that a major technical advancement emerged in the shotcrete industry: the introduction of the “S”-shaped oscillating tube, the first equipment specifically designed for wet-mix shotcrete. Driven by a system of hydraulic pistons, this innovation significantly improved the efficiency and precision of shotcrete application.

In this system, concrete descended from a hopper equipped with a vibrator to maintain its fluidity, while transport cylinders operated alternately to suction or propel the material toward the “S”-shaped oscillating tube. As the tube cyclically aligned with the cylinders, it directed the concrete into a hose with a reduced diameter, which increased the pressure of the shotcrete at the outlet, enhancing its application effectiveness.

The introduction of this equipment marked a milestone in process control, as the ability to regulate the oscillating tube’s cycle speed allowed operators to precisely adjust both the volume and pressure of shotcrete per minute. This advancement not only optimized the quality of the final product but also significantly enhanced system performance, setting a new standard for shotcrete application (Hay, 2017).

### *3.6. 1980s*

The introduction of this equipment represented a milestone in process control, as regulating the oscillating tube cycle speed allowed the operator to precisely adjust both the volume and pressure of shotcrete per minute. This not only optimized the quality of the final product but also significantly improved system performance, setting a new standard for shotcrete application.

According to Dudley and Jolin (2022), by the late 1970s, Laval University in Quebec demonstrated that incorporating air-entraining admixtures into dry-mix shotcrete not only enhanced freeze-thaw durability but also improved resistance to salt-thawing fouling.

However, in the United States, the ACI did not approve the use of air-entraining admixtures in dry mixes, as they failed to meet the regulatory standards at the time. Instead, existing guidelines maintained that dry-mix shotcrete durability was achieved solely through the inclusion of silica fume.

In 1984, Canada saw its first application of silica fume shotcrete during the rehabilitation of a pier in Vancouver's intertidal zone. This project highlighted the significant benefits of incorporating silica fume into shotcrete, both in its plastic and hardened states.

Key advantages included enhanced material cohesion and adhesion, a notable reduction in concrete rebound and slump, as well as improved strength and durability characteristics (Bernardo, Guida & Mecca, 2015).

One of the most significant advancements in shotcrete development during this decade was the introduction of synthetic polypropylene fibers (SnFRS), marking a major milestone in the late 1980s (Dudley & Jolin, 2022). These fibers were classified into two groups:

- Macrofibers, primarily used in wet mixes.
- Microfibers, applied in both wet and dry mixes.

The main benefits of synthetic fibers included enhanced crack resistance, greater heat resistance, and improved toughness and impact resistance. Although polypropylene was the predominant material used in their production, other materials such as nylon, carbon, and polyvinyl alcohol (PVA) were also utilized.

The adoption of these new technologies led to the production of higher-quality shotcrete, characterized by low permeability, reduced leachability, and significantly improved durability. These enhancements resulted from the interaction between the concrete matrix and non-metallic elements, further optimizing shotcrete performance.

The period of decline and unregulated expansion in the 1970s highlighted the need for greater standardization, a process that


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continued into the 1980s, incorporating advancements made through the adoption of new technologies.

Seegebrecht (2017) mentions that this standardization effort was led by institutions such as ACI and ASTM, which played a key role in establishing standards to improve design, application processes, and quality control in shotcrete. Table 1 outlines the standards introduced during this period of regulatory development.

***Table 1.*** *Regulations of the 1980s.*

| Institution | Id | Description | Year | Remark |
|---|---|---|---|---|
| ACI | 506.3R | Guide to certification of shotcrete nozzlemen | 1982 | |
| | 506-66 | Recommended Practice for Shotcreting | 1985 | Replaced by 506R |
| ASTM | C1018 | Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) | 1984 | Published by Subcommittee C09.42 (Withdrawn) |
| | C1140 | Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels | 1989 | Published by Subcommittee C09.23 |
| | C1141 | Standard Specification for Admixtures for Shotcrete | | |
| | C1116 | Standard Specification for Fiber-Reinforced Concrete | | Published by Subcommittee C09.42 |
| | C1102 | Standard Test Method for Time of Setting of Portland-Cement Pastes Containing Quick-Setting Accelerating Admixtures for Shotcrete by the Use of Gillmore Needles | | Withdrawn |

*Source: (Pye, 2006).*

### *3.7. 1990s*

By 1996, air-entraining admixtures had already gained widespread acceptance worldwide. However, their adoption in the United States only began to take hold after research confirmed their effectiveness in enhancing shotcrete performance, particularly in environments exposed to prolonged freeze-thaw cycles.

During this period, alkali-free accelerating admixtures were also developed, primarily to reduce the risks of burns and respiratory issues among operators, thereby improving safety standards in shotcrete applications.

In the regulatory arena, European institutions played a pivotal role in establishing specific standards for shotcrete. In 1996, the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) published the first comprehensive shotcrete standard, covering products, materials, test methods, quality control, and admixtures.

At the same time, the European Committee for Standardization (CEN) Technical Committee 104 created a working group focused on shotcrete, aiming to develop standardized test methods. According to Pye (2006), these efforts were largely based on EFNARC specifications, supplemented by Germany German Institute for Standarization (DIN) 18551 standards - which addressed shotcrete production and quality control - and, to a lesser extent, French Standarization Association (AFNOR) standards.

Meanwhile, in the United States, ASTM continued developing key shotcrete standards, the most notable of which are listed in Table 2.

***Table 2.*** *Regulations from the 1990s.*

| Institution | Id | Description | Year | Remark |
|---|---|---|---|---|
| ASTM | C1117 | Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance | 1994 | Withdrawn |
| | C1385 | Standard Practice for Sampling Materials for Shotcrete | 1998 | Subcommittee C09.46 |
| | C1436 | Standard Specification for Materials for Shotcrete | 2005 | |

*Source: (Pye, 2006).*

### *3.8. 2000s*

In 2000, the first automated wet-mix shotcrete equipment was introduced to the market, following two years of development that began with the creation of the Meyco® Robojet Logica Spray Mobile.

Specifically designed for underground applications, this system featured a computerized concrete spraying mechanism.

The patent was acquired by Inco Limited, which, in collaboration with Meyco® Equipment of Switzerland, further refined the design. This led to the development of the Meyco® Robojet Logica 15, recognized as the first robotic shotcrete equipment (Rispin, 2003).

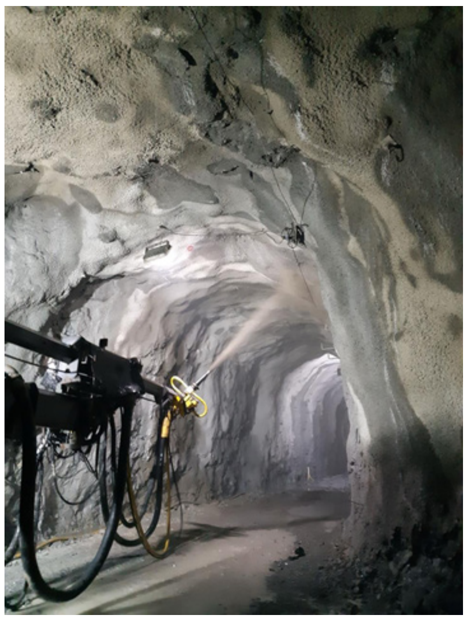
***Figure 6.*** *MEYCO Robojet Logic (Rispin, 2003).*

***Figure 7.*** *MEYCO Robojet Logic (Rispin, 2003).*

Robojet Logica 15 stood out for its integration of advanced mapping and scanning technology, utilizing sensors within its control unit to analyze the work area. Runciman and Newson (2001) explain that this system featured three operating modes: manual, semi-automatic, and automatic.

- In manual mode, the operator controlled all application parameters using a joystick, making it ideal for complex surfaces requiring precise and specialized handling.
- In semi-automatic mode, the operator managed nozzle movement and speed, while the equipment's software automatically adjusted the jet's distance and angle.
- In automatic mode, the computer took full control of speed, distance, and jet angle, shifting the operator's role to that of a process supervisor.

***Figure 8.*** *Tunnel under construction with projection machinery. Source: Prepared by the authors.*



The initial tests of the equipment were conducted at the Mines Research Test Site within an Inco mineral deposit. The results revealed significant benefits, including precise application thicknesses, reduced rebound, enhanced safety, greater operational efficiency, and improved ease of operation.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This breakthrough marked a milestone in shotcrete automation, sparking further research and advancements in the technology. American Shotcrete Association (ASA) Underground Committee (2020) explains that robotic wet-mix equipment operates via remote control, following a structured process:

1. Concrete is loaded into the equipment's hopper.
2. A dual-piston pump propels the material through pipes to the nozzle.
3. At the nozzle, the concrete is mixed with compressed air and additives before being sprayed onto the target surface.

***Figure 9.*** *Slope reinforced with anchors and application of shotcrete.*
*Source: Prepared by the authors.*

As shown in Table 3, new regulations were continuously developed and implemented throughout this decade to standardize evolving shotcrete processes, ensuring its safe and efficient application.

**Table 3.** *Regulations 2000s.*

| Institution | Id | Description | Year | Remark |
|---|---|---|---|---|
| ASTM | C1550 | Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel) | 2003 | Withdrawn 2020 |
| | C1480/ C1480M07 | Standard Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application | 2005 | Reapproved 2012 |
| | C1604/ C1604M05 | Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete | 2005 | Reapproved 2012 |
| | C1398 | Standard Test Method for Laboratory Determination of the Time Setting of Hydraulic-Cement Mortars Containing Additives for Shotcrete by the Use of Gillmore Needles | 2007 | Withdrawn 2010 |
| | C1609/ C1609M12 | Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) | 2007 | Amended 2020 |

*Source: (Pye, 2006)*

### *3.9. From the 2010s*

The year 2010 marked a period of significant advancements in shotcrete techniques, equipment, and materials, with particularly notable progress in admixtures, such as alkali-free accelerators.

Bracamontes (2022) states that throughout this decade, the formulations of these admixtures were refined, improving their applicability in shotcrete while enhancing environmental, industrial, and worker safety. Research conducted during this period confirmed their key benefits, including reduced rebound, early strength development, and minimized cracking, solidifying their status as one of the most widely used components in shotcrete applications.


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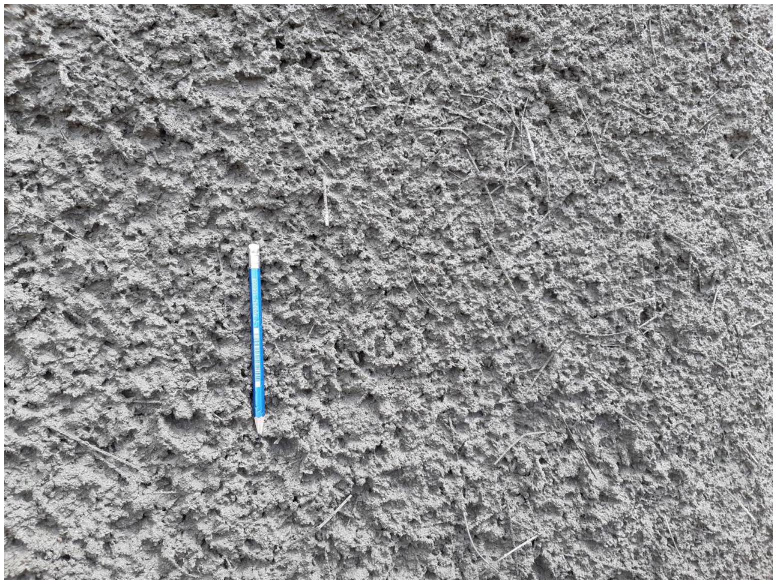
***Table 3.*** *Application of shotcrete on a reinforced slope*

*Source: Prepared by the authors.*

Since 2016, the use of fiber reinforcement in shotcrete has experienced significant growth compared to previous decades. Numerous studies have analyzed the properties and performance of fibers made from various materials, including polypropylene, steel, PVA, nylon, and glass.

The findings highlighted improvements in crack resistance, toughness, and overall shotcrete performance, leading to increased adoption in projects—particularly in tunnel linings and large open-air excavations. This advancement has also contributed to a reduction in the reliance on traditional reinforcements (Ahmad, Alabduljabbar & Deifalla, 2023).

***Figure 11.*** *Texture of fiber-reinforced shotcrete.*



*Source: Prepared by the authors.*

Another notable innovation of this era was the introduction of superabsorbent polymers as an alternative to traditional materials, including additives and supplementary pozzolans. According to Flores (2022), these polymers helped optimize the rheological properties of shotcrete, enabling significant reductions in cement usage, correction of aggregate deficiencies, minimized segregation, and improved workability.

Their primary function is to absorb excess water, converting it into a gel that helps maintain mix consistency and enhance rheological properties. Over time, the polymer gradually releases the absorbed water in liquid form, facilitating the curing process.

Key benefits of superabsorbent polymers include:

- Reduced rebound during application.
- More efficient curing on complex surfaces.
- Compatibility with other additives, particularly superplasticizers.
- Enhanced adhesion and cohesion in shotcrete applications.



https://doi.org/10.24050/reia.v22i44.1883

Although the concept of sustainability had been discussed for years, it gained greater relevance during the 2010s as project stakeholders sought a balance between environmental responsibility and operational efficiency. This shift was driven by growing public awareness, carbon footprint regulations, and the promotion of best practices, all of which influenced the evolution of shotcrete techniques, materials, and equipment.

Jolin y Darveau (2022) states that research on natural fibers demonstrated benefits in both the pumping and spraying processes, as well as in the properties of shotcrete, leading to reduced rebound and increased applied thickness. Additionally, the introduction of fully robotic equipment has helped lower the carbon footprint by replacing diesel engines with electric ones and incorporating hydrostatic systems for improved efficiency (Auen & Lyngroth, 2019).

## 4. Discussion

The evolution of shotcrete from a manual, unstandardized technique to a streamlined process governed by internationally accepted codes and standards represents one of the most significant advancements in construction history. This transition—shifting away from conventional concrete installation toward specialized equipment while simultaneously advancing materials science and technology—is one of the key achievements highlighted in this document.

Once a basic solution primarily used for façade repairs, shotcrete has evolved into a key technology for the construction of complex infrastructure. This paper examined its historical development, highlighting major milestones in its technical evolution and adaptability.

Key advancements include improved application methods and the development of more homogeneous mixtures with enhanced adhesion, strength, and durability. These innovations have been instrumental in integrating shotcrete into large-scale construction projects.

While not all construction processes can be fully industrialized, the technological evolution of shotcrete has underscored the need for continuous refinement to meet growing demands and adapt to historical and industry changes.

In this regard, machinery advancements have played a crucial role in enhancing shotcrete performance. From early manual equipment to advanced technologies like the Robojet, innovations have consistently prioritized efficiency, precision, and safety, while also reducing the risks associated with manual application.

Additionally, the development of more sophisticated pumps and nozzles, designed in accordance with standards from EFNARC, ASTM, and ACI, has elevated quality benchmarks. This progress has also increased the demand for highly trained personnel to ensure optimal results in shotcrete applications.

Simultaneously, advances in materials science, including the incorporation of additives (such as silica fume, superplasticizers, and accelerators) and synthetic and metallic fibers, have significantly enhanced shotcrete properties. These innovations have not only improved compressive strength and durability but have also mitigated issues such as cracking and rebound during application.

As a result, shotcrete has been adapted for a broader range of applications, from slope stabilization to dam lining, effectively meeting the demands of international regulations.

The evolution of shotcrete is deeply intertwined with human history, showcasing its ability to meet specific needs through visionary technological advancements. This paper highlighted how shotcrete has masterfully adapted to the technical and environmental demands of an ever-evolving industry.

Today, shotcrete stands as a symbol of innovation, driven by the integration of cutting-edge materials, precision equipment, and sustainable application methods. These advancements have solidified its role in modern construction, reaffirming its status as a pillar of progress in the field.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT / SciSpace to improve translation and redaction. After using this tool/

service, the authors reviewed and edited the content as needed and assume full responsibility for the content of the publication.

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Revista EIA | https://doi.org/10.24050/reia.v22i44.1883