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The Impact of Advanced Concrete Technologies on Modern Construction and Aesthetics

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Abstract

This paper examines the evolving concrete technology landscape and its impact on the construction industry. With the help of technology making progress in great strides today, the history of construction with concrete is over 2000 years old from those traditional compositions to the new products like high-strength powder concrete, precast concrete, smart concrete. What is brought out in view of nature, therefore, is the applications of precast concrete in architectural designs by virtue of its lightweight and its flexibility and durability in adding beauty to the designs. In addition, the report develops colored concrete as an aesthetic treatment to urban spaces. The nanoparticles are developed into and elaborated as enhancers of microstructural properties of concrete for providing better strength and durability. The paper examines the development in the smart concrete in making it multi-functional and intelligent in reaction to the changes in the environment and its load conditions. The paper also discussed aesthetic techniques in concrete, that is with regards to pigments, patterns and polishing to attain varied and durable finishes. From this point, the paper makes a critical discussion regarding the cutting-edge technologies regarding concrete, and it is evident that the technology could open new potentials for the revolutionary changes in the urban and architectural designs in the same manner as sustainable aesthetic construction practices.

1. Introduction

The need to understand the technology behind various types of concrete, given its crucial role in the construction industry, appears essential for both designers and project managers (Alvansazyazdi *et al.*, 2023; Asli and Arabani, 2022; Hendrickson and Au, 1989). The widespread use of concrete in constructing and producing diverse structures, along with its broad range of applications from ancient times to the present, has positioned it ahead of other building materials (Allen and Iano, 2019). The history of concrete usage dates back approximately 2000 years, with the Egyptians employing a mix of different materials to construct their edifices (Forty, 2013). Furthermore, historical analyses of concrete in architecture reveal its utilization by Roman and early Christian architects, although it was often overlooked during the Middle Ages and Renaissance (Oleson *et al.*, 2014). Today, the field of concrete

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technology has expanded significantly beyond its primary components: cement, aggregates, and water. Following the diversification of its applications, concrete technology now encompasses concepts that surpass those of the past (Makul, 2023).

Among other heterogeneous materials having superior properties over homogeneous materials (Moradi *et al.*, 2021; Moradi and Mehradnia, 2023), The quality of concrete, its efficient use, design versatility, and minimal environmental impact have led to an increasing reliance on this material. Currently, the world produces slightly more than one ton of concrete per person per year, contributing significantly to infrastructure development (Kusuma *et al.*, 2015; Naik, 2020). The widespread use of concrete underscores its critical role in modern society. Research on concrete has traditionally focused on enhancing its compressive strength, given that many of its properties, such as density and permeability, are influenced by this characteristic. However, the expanding use of concrete in urban development has sparked interest in modifying surface treatments to achieve aesthetically pleasing and varied finishes (Mohammed Ali *et al.*, 2024). Advances in technology, coupled with concrete's accessibility, affordability, plasticity, and strength, have diversified its applications, making it more vibrant than ever (Han *et al.*, 2017).

It is crucial for higher education curricula in construction and engineering to incorporate the latest technological advancements in concrete use. This approach ensures that students develop a mindset aligned with technological progress, preparing them for innovative uses of new technologies in the construction industry. Concrete's significance in modern construction techniques is undeniable, as evidenced by its application in interior architecture and furniture design (Feizbahr and Pourzanjani, 2023). The development of high-strength powder concrete, with compressive strengths up to 860 MPa and applied through shotcrete, exemplifies the material's versatility. This paper discusses groundbreaking concrete products, offering readers new perspectives and a comprehensive understanding of their transformative impact on the construction industry (Jo *et al.*, 2010).

2. Precast concrete in interior, exterior and urban design

Precast concrete is a special type of concrete produced in workshop environments using specific molds. It is then transported, ready for installation, in construction projects. Precast concrete is prepared with various characteristics and different raw materials (Senaratne and Ekanayake, 2012; Wang *et al.*, 2020). Looking at the use of concrete types in architecture, precast concrete emerges as an option. Preferred for architectural applications, precast concrete is lightweight and can be easily painted. Moreover, it is highly resistant to wear and corrosion. Architects employ this type of concrete in the exterior implementation of projects. By using special molds, they achieve beautiful and artistic designs, thereby creating stunning visuals (Yang *et al.*, 2024).

These products serve as intermediaries in interior design, creating a harmonious atmosphere when combined with other elements. Moreover, prefabricated concrete products are utilized in designing outdoor spaces (Zhang *et al.*, 2020). Concrete's diverse properties, which vary based on the mold used, enable it to achieve finishes ranging from smooth and simple to detailed and complex. Consequently, its application in outdoor design is more cost-effective than stone and brick, offering superior plasticity compared to other materials. Self-compacting concrete exemplifies the ease of use and flexibility in constructing special structures and enhancing both indoor and outdoor spaces. Concrete's versatility extends to outdoor applications, including pavements, water features, fountains, sculptures, planters, and tables (Okamura and Ouchi, 2003).

In urban environments featuring roads, parks, and promenades, we frequently encounter concrete tables, benches, flower beds, and garbage cans (Ford, 2000). These often lack appropriate color or, if painted, their appearance quality diminishes over time. We typically face the issue of concrete surface corrosion and wear, creating an unsightly view in urban spaces and negatively impacting the observer's experience. Upon initial consideration, the production of colored concrete might seem costly in terms of production and quality, along with concerns about its long-term durability (Kulikova, 2018; Labiapari *et al.*, 2021). However, technological advancements in manufacturing these concretes at lower costs and with high durability challenge this outdated perception, showcasing the progress in modern concrete technology (Makul, 2020, 2023).

The incorporation of ceramic and metal pigments represents a novel approach in colored concrete production. These pigments enable the creation of concrete in vibrant colors such as blue, red, black, yellow, green, and orange. The fine granularity of ceramic pigments ensures a uniform and homogeneous distribution within the concrete, enhancing its strength and reducing permeability (Ardit *et al.*, 2023; Pfaff, 2008). Moreover, the pigment constitutes a minimal percentage of the total composition, thus not significantly impacting the cost. The final price of these concretes remains comparable to that of standard concrete. About 1 to 3% of the desired pigment is added during processing, with the remaining steps mirroring those of conventional concrete production (Pfaff, 2008). Notably, for large objects, only the surface layer may be colored, leaving the interior mass in the natural concrete color (Jesus *et al.*, 2023).

The benefits and applications of these concretes extend to street markings, urban concrete structure painting, beautification of roads, and structural longevity enhancement. They are also utilized in sports fields and stadiums for coloring spectator areas, among other uses. These concretes offer distinct aesthetic advantages and are cost-effective by eliminating the need for maintenance and repainting (Huston, 2016).

Colored concrete is primarily utilized in the production of urban furniture. However, considerations such as the weight of the finished products are crucial, especially for items like garbage bins, mud pits, or movable tables that require transportation, in addition to the need for high compressive and tensile strength (Brownell, 2010).

Advancements in concrete technology now allow to produce lightweight concrete, with specific weights less than 1000 kg/m^3, while still maintaining high resistance. These lightweight products are highly suitable for urban furniture due to their reduced weight and increased plasticity. Lika or industrial pumice, obtained by heating clay particles in rotary kilns, serves as a key lightweight aggregate in this concrete type (Thienel *et al.*, 2020). The presence of voids within these aggregates contributes to their low specific weight, allowing for their use in high-strength concretes with low water-cement ratios by incorporating microsilica and lubricants (Kockal and Ozturan, 2011).

However, the increased porosity, a byproduct of using such materials for weight reduction, necessitates measures to decrease porosity to enhance strength and minimize permeability—critical issues that lead to the degradation of urban furniture concrete due to high permeability and lack of resistance to changing weather conditions, which causes surface corrosion and rapid deterioration (Blazy *et al.*, 2022; Gupta and Kua, 2020).

Addressing these concerns involves reducing the diameter of Lika aggregates (when creating lightweight concrete) and optimizing the size of natural aggregates used. The strategic use of additives plays a pivotal role in achieving concrete with desired performance and durability. For instance, aerated bubble additives significantly enhance resistance to environmental heating and cooling cycles, protecting the concrete surface from corrosion and wear (Cherry and Green, 2021). Additionally, the incorporation of pozzolanic materials, such as microsilica—with particles approximately 1/100 the diameter of cement particles—and nanosilica, which is more effective than microsilica in reducing particle size, proves beneficial. These materials replace a portion of the cement in the concrete mix, improving overall quality (Abhilash *et al.*, 2021; Alvansazyazdi *et al.*, 2023; Feizbahr *et al.*, 2020).

Thus, through the judicious application of additives and pozzolanic materials, alongside other components in standard, lightweight, colored, and polymer concretes, it is possible to produce high-quality products. This approach addresses concerns related to durability, as well as corrosion and wear of external surfaces and internal reinforcements within the structures.

Figure 1. exposed colored concrete in pavement and building walls (Naganna *et al.*, 2021).

3. Nanoparticles in concrete

The integration of nanoparticles in various types of concrete significantly enhances its properties by addressing the microstructural characteristics of concrete, which includes nano-sized voids. Utilizing nanoparticles to fill these minuscule pores within the cement paste can markedly improve the concrete's strength and durability (Abhilash *et al.*, 2021).

In scenarios where external environmental factors act as destructive agents, the permeability of concrete becomes a critical factor influencing its integrity and the rate at which it deteriorates. The application of nano powders, such as hydrated calcium nanoparticles, proves highly beneficial in this context. Additionally, these particles can alter the chemical makeup of the concrete mixture through their reactive capabilities, presenting an innovative approach to enhancing concrete's performance (Mydin *et al.*, 2023; Nejad *et al.*, 2018).

A noteworthy example in this domain is nano silica. Research indicates that incorporating amorphous silica particles, with dimensions below 100 nanometers, substantially boosts concrete's reliability (Abhilash *et al.*, 2021). Furthermore, the quantity of nano silica required to achieve effects similar to those of silica fume is considerably lower, offering a distinct advantage in its application from multiple perspectives. Beyond this, nano silica's inclusion in concrete mixtures yields additional benefits across various concrete properties, enhancing formulations such as self-compacting concrete or high-strength concrete (Khan *et al.*, 2022; Safavigerdini *et al.*, 2023). Overall, the employment of nanoparticles in concrete, irrespective of their direct involvement in hydration reactions, plays a pivotal role in refining the microstructure and enhancing the overall reliability of concrete. Their physical presence effectively fills the tiny voids in cement, further solidifying the concrete's structural integrity.

4. Smart concrete

Smart materials can exhibit unique characteristics like shape memory, self-healing, or changing color, making them adaptable and functional in various applications (Khorramabadi and Ferdosi, 2023). Smart concrete represents the development and construction of concrete that not only offers high performance and resistance but also features multifunctionality and intelligence. It is a new generation of concrete materials capable of responding to external factors, such as load and environmental conditions (Makul, 2020).

Smart concrete can also be extensively used in constructing urban furniture, offering a wider perspective in the field of architecture, whether used independently or in combination with colored, light, and polymer concrete. This type of concrete falls into the category of fine-grained concrete that changes color in response to variations in light or weather conditions. One of its advantages includes the widespread availability of raw materials (Krejcar *et al.*, 2019).

Smart concrete possesses capabilities such as altering designed images or symbols, adapting its color to blend with the surroundings when necessary, and maintaining buoyancy on the water surface. These features make it suitable for designing urban sculptures, monuments, and building facades. Additionally, it offers significant benefits for street pavements by enhancing visibility at night, showcasing its versatile applications.

5. Aesthetic techniques in concrete

Applying pigments and creating a special spatial shape by examining and targeting the color and its application (Osman, 2012):

- The variety of colors, the optimal durability of painted surfaces, and the non-fading of colors in a long period of time are among the benefits of this method.
- The types of colors used in this technique are shown in the next diagram. Using this method on the floor of areas, streets, sidewalks and even vertical surfaces such as walls.

Applying patterns on the concrete surface (Oliveira Santos *et al.*, 2019):

- Painting desired patterns on concrete surfaces and making them homogeneous surfaces.
- Using similar patterns of other materials such as brick, stone and wood in the patterning method of surfaces.
- Selection of patterns by designers and architects and according to the type of use of the surfaces.
- Using them on the floor of areas, streets, sidewalks and even vertical surfaces such as walls.

Engraving on concrete (Jiang *et al.*, 2021):

- A method like embossing concrete that requires special tools and equipment in order to cut and add graphic designs to all types of concrete.

Polishing concrete (de Matos *et al.*, 2018):

- Applying this method in polishing fresh concrete surfaces, so that the desired surface looks like marble. The use of this method in administrative offices, commercial and public places, especially the exhibition, is to enhance the concrete surfaces.

Granular concrete or finishing surfaces with visible aggregates (Javid and Nejad, 2017; Shen *et al.*, 2011):

- It is used in the design of relatively large outdoor spaces.
- Smoothing of concrete surfaces is done using the necessary tools and equipment, and then it becomes possible to embed stone materials on smooth surfaces. Also, the possibility of using colored natural stones, recycled colored glass, as well as decorative shells, gives these surfaces a special effect.

Stenciling concrete surfaces (Dubal and Mohite, 2016):

- This method is to add simple and complex designs to concrete, which is possible by using frames and a combination of different lines and roles in the design of the desired surfaces.
- The use of this method in the design of the floor of areas, streets, buildings, and also in the design of vertical surfaces such as partitions, is proposed as a cost-effective method.

Conclusion

The exploration of advanced concrete technologies presented in this paper underscores the material's role in shaping the future of construction and urban design. By transcending traditional limitations, innovative concrete products like precast, colored, and smart concrete, along with the strategic use of nanoparticles, have opened new horizons for architects and engineers. Precast concrete, with its versatility and efficiency, serves as a cornerstone for modern architectural applications, offering a sustainable alternative with reduced construction times and enhanced aesthetic appeal. Colored concrete, through the application of ceramic and metal pigments, provides an opportunity to infuse urban spaces with vibrant colors and textures, challenging previous perceptions about concrete's aesthetic limitations and durability.

The integration of nanoparticles into concrete formulations marks a significant advancement in enhancing the material's microstructural properties, leading to improvements in strength, durability, and environmental resistance. This nano-engineering approach not only bolsters concrete's traditional attributes but also introduces new functionalities, such as self-cleaning surfaces and enhanced mechanical properties. Smart concrete emerges as a futuristic material, capable of adapting its properties in response to external stimuli, thereby offering innovative solutions for dynamic architectural and urban applications.

The paper's examination of aesthetic techniques further illustrates the creative potential of concrete, showcasing methods such as pigmentation, patterning, engraving, and polishing. These techniques enrich concrete's visual and tactile qualities, elevating it from a mere structural component to a key element of design expression.

In conclusion, the advancements in concrete technology highlighted in this study illustrate the material's evolving role from a fundamental building block to a versatile, intelligent, and aesthetically diverse medium. The continuous innovation in concrete composition, properties, and applications not only enhances its performance and sustainability but also redefines its contribution to the built environment. As the construction industry moves towards more sustainable and aesthetically pleasing materials, the insights provided by this paper contribute significantly to the discourse on modern construction materials, offering valuable perspectives for future research and application in architectural and urban development.

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