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SELF-CLEANING CEMENTITIOUS COMPOSITES: CURRENT DEVELOPMENTS, CHALLENGES, AND FUTURE OPPORTUNITIES

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ABSTRACT:
Self-cleaning cementitious composites are one of the most functional building materials that have recently gained significant importance in order to enhance the aesthetic durability, environmental characteristics and service life of building and infrastructure. The materials are intended to prevent dust, organic impurities, dirt and airborne contaminants from settling on open surfaces by photocatalytic or superhydrophobic effect or by a combination of both effects. Recent developments have been based on the introduction of nanomaterials (titanium dioxide, silica-based modifier, and surface treatment) in cement-based matrices, which are not only mechanically strong but also active on the surface. Even with laboratory success, there are the challenges of durability, cost, dependence on weather conditions, compatibility with existing construction practices, as well as long-term maintenance performance that yet to be overcome in practice. The field is shifting from proof-of-concept research to optimization for real-world applications, notably in facades, pavements, tunnels and urban air-purifying structures. This paper summarizes the latest advances in SCCs, highlights the significant technical and practical challenges, and outlines potential future prospects for increased use. The development of materials, standard testing procedures, and life-cycle assessment will be essential to making these new composites a viable construction option, it's claimed.

KEYWORDS: self-cleaning cementitious composites, photocatalytic concrete, hydrophobic surfaces, nanomaterials, sustainable construction.

INTRODUCTION

The use of cementitious composites as the most popular construction materials in the world is due to their versatility, low cost and structural capacity. Conventional cement-based surfaces, however, tend to discolours, dust deposit, grow biological organisms and stain chemically over time. These effects affect the visual quality, maintenance requirements and can even lead to degradation of the surface. On the other hand, self-cleaning cementitious composites, which can keep the surface of the material cleaner with a minimum requirement of external services, have drawn attention as advanced materials.

The idea of self-cleaning behaviours of cement-based materials is mostly inspired from the natural and chemical processes. Some systems involve photocatalysis, in which the organic contaminants are destroyed by a light-activated particle. Some rely on superhydrophilicity, which causes the water to roll off and take dirt with it. There is also an increasing amount of research focusing on hybrid systems which use both mechanisms. Self-cleaning cementitious composites are gaining significance due to the need for more sustainable and low maintenance materials in urban environments.

1.1 Scope of the Review

This paper reviews the current condition of SCCC, and gives focus to materials, mechanisms, applications and challenges to overcome (Liu et al., 2024). The relationship between functional performance and structural requirements are given special consideration, as cementitious materials should have sufficient strength, durability, and usability for engineering applications.

2 Current Developments in Self-Cleaning Cementitious Composites

In recent years, the functional abilities of concrete, mortar and cement paste, in addition to their structural properties, have been extended beyond their usual scope by the development of self-cleaning cementitious composites. These materials are no longer considered to be merely load bearing materials, but are now treated as active surfaces that can react with the environment around them in the current research. In urban construction, the self-cleaning function is particularly relevant as it is the exterior surfaces exposed to cement-based materials that are constantly impacted by soot, dirt, oily deposits, biological growth and pollutants in the air. In order to overcome the above problems, recent research on self-cleaning cementitious composites can be broadly categorized as photocatalytic, hydrophobic or superhydrophobic, and hybrid multifunctional (Rodríguez-Alfaro et al., 2023). All of these methods rely on different mechanisms and each is being optimized to not only achieve better cleaning results but to also be more durable, compatible for cement hydration, and more suitable for large scale application in the field of engineering.

2.1 Photocatalytic Cementitious Composites

One of the most widely studied materials for self-cleaning is photocatalytic cementitious composites. They are mainly developed by embedding semiconductors such as titanium dioxide in cement matrices. Under the influence of ultraviolet light, the titanium dioxide turns into an activated form, generating the reactive oxygen species like hydroxyl radicals and superoxide ions (Ramadan et al., 2023). They can break down the organic contamination, stains, microorganisms and air pollutants which settle on the concrete surface. Therefore, the material can help to keep surfaces cleaner for longer and participate in environmental restoration in polluted urban areas as well.

The main reason for the attraction to titanium dioxide is that it is a relatively cheap material with a high photocatalytic activity, it is chemically stable and has low toxicity (Kalinowski et al., 2023). It has been introduced into cementitious systems through a variety of methods such as surface coatings, slurry layers, thin cement-based overlays, and through direct bulk addition during mixing. Surface coating techniques are more successful in the short-term, because the active particles are still exposed to light and contaminants. By contrast, bulk incorporation can result in the trapping of a portion of the particles in the matrix, which will decrease the immediate surface activity but will increase the ability to retain the photocatalyst over time as particles abrade or weather.

The other important aspect of development is particle size and dispersion. Nano-sized particles of TiO_2 are generally found to be superior to the micro-sized particles because of the higher surface area of the nano-sized particles, which results in a higher photocatalytic activity. But nanoparticles have a tendency to clump together, potentially limiting their effectiveness and affecting the hydration process of cement when they're not evenly distributed. One way to overcome this limitation is through the use of ultrasonic dispersion, surfactant-assisted mixing and surface modified nanoparticles. The approaches are focused on enhancing the activity of the photocatalyst and its compatibility with fresh and hardened cementitious systems.

Recent studies have also extended beyond the traditional use of titanium dioxide. One of the biggest drawbacks of conventional photocatalytic systems is that they require ultraviolet radiation to work, which is a problem because it is difficult to obtain. There is a search to find ways to overcome this limitation to make such photocatalytic systems work with visible light. Because only a small portion of solar energy is in the ultraviolet spectrum, materials that work under visible light would work better in the typical outdoor application and might be useful in a partially shaded application. Further research in this area is particularly relevant to practical application in urban environments, where direct sunlight may not be present.

However, there are still several interacting variables which influence the self-cleaning efficiency of photocatalytic cementitious composites. They consist of the type of binder used, the water-cement ratio, porosity, curing condition, pollutant type, humidity, and light intensity. Thus new developments are moving more and more towards optimizing the system than just adding it on (Guo et al., 2022). The aim is to develop photocatalytic composites, which are both catalytically active and have favourable mechanical properties in practical use.

2.2 Hydrophobic and Superhydrophobic Composites

Another noteworthy research direction is on hydrophobic and superhydrophobic cementitious composites. Hydrophobic materials do not break down contaminants as do photocatalytic systems, they are dependent on the control of surface wettability. Their purpose is to give the surface a low energy state and a desired surface roughness so that water droplets beading up and rolling off rather than spreading. The droplets roll across the surface and collect dust and loose particles, which results in cleaning of the material via a rolling-water effect.

This concept has been greatly inspired by the lotus leaf effect (which incorporated micro and nan surface texture), and being water-repellent, it also helps to not accumulate contamination buildup. In the case of cementitious materials the ability to generate such behaviours is more challenging due to the inherent porous, rough and hydrophilic nature of the substrate. Therefore, the focus of current developments is on the modification of the surface chemistry, the surface texture or both (KISS, 2022). Typical techniques used are treatment with silane and siloxane compounds, deposition of fluorinated agents, incorporation of nano-silica, etching or coating to create hierarchical surface structures.

Another benefit of the hydrophobic systems is that they are less light dependent. Therefore they are especially recommended for applications such as building facades, walkways, interior architectural panels etc. where the photocatalytic effect might be less pronounced. Hydrophobicity can also prevent water absorption, limit chloride penetration and minimize freeze-thaw damage, in addition to self-cleaning. Therefore, many studies consider hydrophobic self-cleaning surfaces as aesthetic enhancements and protective durability treatments.

The durability of the hydrophobic performance is becoming a topic of current research. However, in practice, superhydrophilicity can be compromised due to abrasion, exposure to UV rays, chemical attack, wetting-drying cycles, or the obstructions of pores caused by dust and salts. Materials such as cementitious in concrete pavements, exterior cladding and public infrastructure are especially susceptible. In recent years, therefore, the focus is on coatings with wear resistance, chemically bound surface treatments and systems in which the water repellence is ensured from the inside. There are also some researchers who investigate the development of self-healing or reconfigurable surfaces with hydrophobic properties, which will regain their properties once they are damaged.

A second significant advancement is the desire for an evenness balance with mechanical strength. Rough hierarchical textures can enhance the repellence but can also generate weak areas or decrease the adhesion of the coating if improperly designed. So material scientists are making efforts towards optimized surface architectures, which can ensure high water repellence without compromising the durability and appearance of the substrate. The successful engineering use of the hydrophobic cementitious composites is closely related to this balance.

2.3 Hybrid and Multifunctional Systems

The most advanced level of self-cleaning cementitious composites development are hybrid and multifunctional systems. These materials have two or more useful mechanisms that are integrated to create a single engineered surface or matrix, and typically involve both photocatalytic degradation and hydrophobic water repellence (Moro et al., 2022). This is a combination of the two approaches in order to address their respective limitations. In this system, photocatalysis would be able to decompose the organic contaminants that are attached to the particles, and hydrophobicity would help remove any waterborne contaminants. These in combination can give rise to more stable and flexible self-cleaning behaviours over a broad spectrum of environment.

Given that it is evident that the ongoing development of hybrid systems is an expression of a wider shift in research of cementitious materials. The concrete is now being designed to meet multiple purposes for structural performance as well as environmental, hygienic and maintenance benefits. A self-cleaning function is frequently combined with other beneficial functions, such as antimicrobial, anti-fouling, de-polluting, thermal, or even aesthetic colour stability. In the case of public buildings or anything like a hospital, tunnels, transportation corridors, and particularly high-value architectural surfaces, this is especially important because cleanliness and surface performance are tied together.

One of the key areas of recent research is the ability to fuse functions without causing interferences between them. For instance, a very hydrophobic coating can be achieved and the surface wetting may be minimal, limiting pollutant contact with the photocatalytic particles. On the other hand, certain photocatalytic surface can progressively break down the organic compounds applied to impart hydrophobicity (Maqsood and Garg, 2023). Researchers are working on layered coatings, composite nanostructures, and chemically stable coupling methods that will retain both functions, to address this problem. The design challenge is then not only to successfully combine several effects, but to have them be compatible for long term service.

The application-specific design is also highlighted in recent advances of multifunctional systems. A hybrid configuration for the sun and rain exposed façade may be different from a pedestrian pavement, which is abraded and darted. This has led to a more targeted development of materials, in which the microstructure, treatment depth and surface chemistry are chosen depending on the potential environmental exposure. This application-oriented design will most certainly have a major impact on this next generation of self-cleaning cementitious composites.

In general, it is seen from the current developments that the self-cleaning cementitious composite materials are progressing from laboratory innovations to more widely engineering relevant material systems (Zailan et al., 2022). The ongoing challenge is to transform the concept for a functional structure into a material that is durable, scalable and economically viable.

3 Major Challenges

Self-cleaning cementitious composites offer great promise, but there are several challenges that prevent their use. Long term durability is a big worry. The abrasion, carbonation, cracking, freeze-thaw, and chemical attack on cementitious surfaces in real environments are the factors that were considered. These conditions can decrease the efficiency of photocatalytic particles or affect hydrophobic coatings.

Another issue is the compromise between function and mechanical properties. Dosages of high concentration of nanoparticles or surface modifiers can change hydration, porosity, workability, and bond properties (Zhao et al., 2025). When not managed properly, these modifications can decrease the compressive strength or increase the cost without providing consistent field performance.

Lack of standardization too. The difficulty in comparing results from many published studies is due to the use of different test methods, contamination sources, curing regimes, and weather conditions. This means that what works in the lab does not always manifest itself in the field. Implementation presents further challenges in terms of economic viability, especially for larger infrastructure projects, where the initial costs are a key determinant.

4 Future Opportunities

The development of self-cleaning cementitious composites will rely on the optimization of materials and the validation of their behaviours under realistic service conditions in the future. Long-term behaviours could be vastly improved by more durable nanostructured additives, improved methods of dispersion and self-renewing surface treatments. Growth of visible-light active photocatalysts is particularly promising due to the ability to perform beyond strong ultraviolet exposure.

New opportunities for digital material design and life cycle thinking will also arise. Microstructural modelling, environmental simulation and pollution and durability prediction tools can be used to create composites for specific climate and pollution conditions (Wen et al., 2025). At the same time, life-cycle cost analysis may show that the savings in cleaning and maintenance costs, environmental impacts, and other costs offset the increased capital expense.

4.1 Application Potential

Potential uses encompass architectural facades, highway barriers, tunnel linings, roof panels, precast decorative elements and urban pavements. In cities with high levels of pollution they can offer both aesthetic and environmental value (Wet wet et al., 2023). They could be an important direction for future research and commercialization for their integration with green building strategies and smart urban infrastructure.

5 CONCLUSIONS

The development of self-cleaning cementitious composites is a major step forward in the development of sustainable construction materials. These materials can lower soiling and boost visual durability and even aid in environmental remediation via photocatalytic, hydrophobic, and hybrid methods. Nevertheless, there are still key questions of durability, standardization testing, cost and field reliability that have yet to be addressed. The potential of this technology is based on the creation of consistent, strong, multi-functional and economically viable systems to operate in real service conditions. Focusing on the inter-disciplinary research, the potential of self-cleaning cementitious composites in the future infrastructure and building materials as an important research field is being developed.

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