International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 10 | Oct 2026 www.irjet.net p-ISSN: 2395-0072

A Critical Review of Silica Fume, Graphene Oxide and Titanium Dioxide Modified Conventional Concrete: Mechanical, Durability, Microstructural and Functional Performance

Jatin Verma[1], Kavish Verma[2]

[1]*UG Student, Department of Civil Engineering, D. A. V. Institute of Engineering and Technology, Jalandhar, Punjab, India*

[2]*Civil Technologist, MPE a division of Englobe, Medicine Hat, Alberta, Canada*

Abstract - *The growing demand for high-performance and sustainable concrete has encouraged the investigation of advanced materials to improve the mechanical, durability, microstructural, and functional properties of conventional concrete. Among these, silica fume (SF), graphene oxide (GO), and titanium dioxide (TiO_2) have attracted considerable attention due to their distinct mechanisms of action. SF enhances pozzolanic reactions, particle packing, and pore refinement, while GO can influence hydration, interfacial bonding, microstructural development, and crack propagation. TiO_2 offers additional photocatalytic functionality, including self-cleaning and the degradation of selected atmospheric pollutants. This review critically evaluates SF-, GO-, and TiO_2-modified conventional concrete, focusing on fresh properties, mechanical performance, durability, microstructure, and functional characteristics. The individual contributions of these materials are examined alongside available evidence on their binary and multi-material combinations, considering dosage, dispersion, mixture composition, and incorporation methods. The literature indicates that performance depends strongly on these factors and that improvements in one property may involve trade-offs in others. SF primarily contributes to matrix densification, GO influences hydration and crack development, and TiO_2 provides photocatalytic activity dependent on surface accessibility and exposure conditions. Key research gaps include the optimization of multi-material combinations, dispersion strategies, interactions between constituent materials, long-term durability, and balancing mechanical performance with photocatalytic efficiency. This review paper provides a foundation for the future research into multifunctional conventional concrete incorporating SF, GO, and TiO_2.*

Key Words: Conventional concrete; Silica fume; Graphene oxide; Titanium dioxide (TiO_2); Mechanical properties; Durability; Multifunctional concrete.

1. INTRODUCTION

The concrete is one of the most extensively used construction materials worldwide because of its availability, versatility, high compressive strength, and ability to be produced in a wide range of structural forms. Despite these advantages the conventional cement-based concrete continues to face challenges associated with cracking, limited tensile resistance, undesirable transport of water and aggressive agents, durability deterioration and the environmental burden associated with cement production. These limitations have encouraged the development of modified cement-based materials incorporating supplementary cementitious materials, micro-scale additives, and nano-scale modifiers to improve specific performance characteristics of concrete. Consequently, considerable research has focused on modifying the cementitious matrix to enhance mechanical performance, durability, microstructural characteristics, and, increasingly, additional functional properties.

Silica fume (SF) is a widely investigated supplementary cementitious material because of its extremely fine particle size and high content of amorphous silica. Its incorporation into cement-based concrete can promote pozzolanic reactions and particle packing, resulting in pore refinement, matrix densification, and modification of the interfacial transition zone. These mechanisms can contribute to improvements in compressive, tensile, flexural, and durability-related properties under appropriate mixture and curing conditions **(Siddique, 2011; Khan and Siddique, 2011)**. However, the performance of SF-modified concrete is strongly dependent on factors such as replacement level, water-to-binder ratio, mixture composition, curing and the use of chemical admixtures. Higher SF contents may also increase water demand and adversely affect workability when the mixture is not appropriately mixed. Therefore, the benefits of SF cannot be evaluated independently of its dosage and the characteristics of the surrounding cementitious system.

Alongside conventional cementitious materials and advances in nanotechnology have introduced new approaches for modifying cement-based composites. Graphene oxide (GO) is a two-dimensional carbon-based nanomaterial which contains oxygen-bearing functional groups and a high specific surface area. These characteristics enable GO to interact with cement hydration products and influence hydration, pore structure, interfacial characteristics, crack development,

and mechanical performance. Reviews of GO cement composites have reported potential improvements in several performance characteristics, while also emphasizing the importance of dosage, dispersion, mixing procedure, and material characteristics **(Suo et al., 2022).** Unlike SF which is commonly incorporated as a supplementary cementitious material at relatively higher replacement levels, GO is generally used as a low-dosage nano-scale modifier. Its high surface area also makes it susceptible to agglomeration, which can reduce its effective dispersion and limit the expected benefits. Consequently, the influence of GO depends not only on its nominal dosage but also on the effectiveness of its dispersion within the cementitious matrix.

Titanium dioxide (TiO_2) represents another approach to modifying cement-based materials because its principal significance extends beyond conventional mechanical and microstructural modification. TiO_2 can provide photocatalytic functionality under suitable light conditions, enabling cementitious surfaces to participate in the degradation of selected pollutants and organic contaminants. Accordingly, TiO_2-containing cementitious materials have been investigated for applications such as self-cleaning surfaces, pollutant-reducing materials, and functional infrastructure **(Folli et al., 2012; Hamidi and Aslani, 2019)**. The effectiveness of TiO_2 photocatalysis is influenced by several factors which includes particle characteristics, dosage, distribution within the cementitious matrix, accessible surface area, surface condition, light exposure, and the transport of reactants and products to and from the photocatalytic surface. Thus, incorporating a higher amount of TiO_2 do not necessarily results in a proportional improvements in photocatalytic performance. The interaction between TiO_2 particles and the developing cement matrix must also be considered when evaluating its functional performance **(Castro-Hoyos et al., 2022).**

The three materials therefore represent different mechanisms for modifying conventional cement-based concrete. SF primarily contributes through pozzolanic reaction and particle-packing effects that can refine the pore structure and make the cementitious matrix denser. GO primarily functions as a nano-scale modifier capable of influencing hydration, microstructural development, interfacial bonding, and crack propagation. TiO_2 can introduce photocatalytic functionality in addition to its possible effects on microstructure and mechanical properties. These differences are important when comparing their reported performance because an improvement in one property does not necessarily result in simultaneous improvement in all other properties. For example, increased matrix densification may enhance strength and reduce the transport of water or aggressive ions, while simultaneously increasing water demand and affecting workability. Similarly, increasing the dosage of a nano-scale material may not produce proportional improvements if particle agglomeration becomes significant. Therefore, the performance of SF, GO, and TiO_2 should be considered in relation to dosage, dispersion, mixture composition, curing conditions, and the specific property being evaluated.

Existing research has extensively investigated these materials individually, with numerous studies and reviews addressing silica-fume-modified concrete, GO/cement composites, and TiO_2-based photocatalytic cementitious materials. In addition, research has begun to examine combinations of different materials, including the combined use of GO and SF, where the interaction between nano-scale modification and silica-fume-related matrix densification has been investigated **(Abdullah et al., 2021).** Such studies indicate that the effects of combining materials cannot necessarily be predicted by simply adding their individual contributions. The simultaneous presence of multiple fine or nano-scale constituents may influence workability, dispersion, hydration, pore structure, interfacial characteristics, and the accessibility of functional particles. Consequently, evidence from individual material systems provides an important foundation, but it does not by itself establish how different modification mechanisms will interact when incorporated into a common cementitious system.

A more integrated assessment is therefore required to synthesize the available evidence concerning the individual and combined effects of SF, GO, and TiO_2 in conventional cement-based concrete. Particular attention is required to understand the relationships among material dosage, dispersion, hydration, pore structure, mechanical performance, durability, and functional behavior. Such an assessment is also important for identifying potential complementarities as well as possible conflicts between matrix densification, nano-scale modification, and photocatalytic functionality. Rather than assuming that the effects of the three materials are additive, their interactions and the conditions governing their effectiveness need to be critically examined.

Accordingly, this review critically examines the available research on SF-, GO, and TiO_2 modified conventional cement-based concrete. This review evaluates reported effects on fresh properties, mechanical performance, durability, microstructural characteristics, and functional behavior. It compares the mechanisms through which these three materials influence the cementitious matrix. The emphasis is placed on the effects of material dosage and dispersion, the relationship between microstructural modification and macroscopic performance and the available evidence concerning binary and multi-material incorporation. This review further identifies inconsistencies and limitations in the existing literature, including uncertainties associated with optimum proportions, dispersion and mixing techniques, material interactions, long-term performance, and the balance

between mechanical, durability, and photocatalytic properties. Based on these findings the future research directions are proposed for the systematic development and evaluation of multifunctional conventional concrete incorporating SF, GO, and TiO_2.

2. LITERATURE REVIEW

2.1 Silica Fume in Conventional Cement Concrete

Silica fume (SF), also known as microsilica, is a highly reactive supplementary cementitious material consisting predominantly of very fine amorphous silica particles. Its extremely small particle size and high specific surface area allow it to influence concrete through both physical and chemical mechanisms. The physical filling effect of SF improves particle packing and reduces the size and connectivity of pores, while its pozzolanic reaction with calcium hydroxide generated during cement hydration contributes to the formation of additional calcium silicate hydrate (C-S-H). These mechanisms can result in matrix densification and refinement of interfacial transition zone (ITZ).

Siddique (2011) reviewed the hardened properties of silica-fume concrete and reported that SF can influence compressive strength, splitting tensile strength, flexural strength, porosity, creep, and shrinkage. The review attributed the improved performance primarily to the combined effects of pozzolanic activity and physical particle packing. Similarly, **Khan and Siddique (2011)** reviewed the durability performance of SF concrete and reported beneficial effects on permeability, chloride-ion transport, corrosion resistance, sulfate resistance, carbonation, freeze–thaw resistance, and alkali–aggregate-related behavior. The authors emphasized that the refinement of the pore structure and improvement of the cement paste–aggregate transition region are important mechanisms responsible for these effects.

However, the influence of SF is not universally positive and is strongly dependent on mixture composition. The very fine particles increase the surface area that must be wetted, which can increase water demand and reduce workability when an appropriate water-reducing admixture is not used. Therefore, increasing the SF content does not necessarily result in a continuous increase in concrete performance. Experimental research has demonstrated this dependence. For example, **Adil et al. (2020)** investigated SF in pervious concrete and reported that changes in SF content influenced paste rheology, workability, void content, strength, and durability. In their particular mixture system, approximately 5% SF provided favorable overall performance, illustrating that the effective dosage depends on the characteristics and intended performance of the concrete rather than on SF content alone.

The influence of SF is also associated with the water-to-binder ratio, cement characteristics, curing regime, aggregate characteristics, and chemical-admixture dosage. Consequently, results obtained at one replacement level or mixture proportion cannot necessarily be directly generalized to other concrete systems. This is particularly important when SF is considered together with nano-scale materials because the simultaneous incorporation of several fine constituents may further influence water demand, rheology, dispersion, and particle packing. Thus, the role of SF in a multi-material system should be evaluated not only in terms of its individual pozzolanic contribution but also in relation to its interaction with other constituents.

2.2 Graphene Oxide in Cement-Based Materials

Graphene oxide (GO) is a two-dimensional nanomaterial that is carbon-based containing oxygen-bearing functional groups, including hydroxyl, epoxy, carbonyl, and carboxyl groups. Its high specific surface area and chemical functionality allow GO sheets to interact with cement hydration products and modify cementitious microstructure. Unlike SF, which is generally used as a supplementary cementitious material at relatively higher replacement levels, GO is commonly incorporated at very low dosages and acts primarily as a nano-scale modifier.

Suo et al. (2022) reviewed the performance, functionality, mechanisms, and prospects of GO/cement composites and reported that uniformly dispersed GO can improve mechanical performance and influence transport properties. The review also identified GO dispersion and long-term performance as important research challenges. A separate systematic review of GO in cementitious composites examined a large body of published research and identified GO as a potential nano-filler, crack-arresting agent, and nucleation site for cement hydration. These findings indicate that the influence of GO extends beyond simple particle filling and may involve changes in hydration and microstructural development.

Experimental studies provide further evidence that the effect of GO depends strongly on its dosage and dispersion. For example**, The Study by Effect of Graphene Oxide on Rheology, Hydration and Strength Development of Cement Paste (2020)** investigated well-dispersed GO at several dosages and showed that the dispersion procedure and superplasticizer dosage were important factors governing the behavior of GO-containing cement paste. The study reported that well-dispersed GO at an appropriate low dosage could improve fresh and hardened properties, while higher GO contents required greater attention to dispersion and admixture requirements.

Jing et al. (2020) further investigated the role of oxygen-containing functional groups by comparing GO and reduced GO in cement composites. Their results indicated

that the original GO could enhance hydration and compressive strength, with the oxygen-containing functional groups contributing to its interaction with the cementitious system. The study also associated GO incorporation with microstructural refinement, filling of micro-pores, and modification of hydration products.

The importance of dispersion has also been demonstrated experimentally by studies examining GO in alkaline cement environments. Calcium ions and the highly alkaline pore solution can promote GO agglomeration, thereby reducing the effective surface area available for interaction with the cement matrix. A study on optimizing GO dispersion in cement mortar reported that the dispersion process significantly influenced the resulting properties and that an appropriate dispersing system could maintain GO separation and improve the mechanical performance of the mortar. These findings demonstrate that nominal GO content alone is insufficient for comparing different studies because the actual effectiveness of GO depends strongly on whether the sheets remain uniformly distributed throughout the cementitious matrix.

The literature therefore indicates that GO can influence cement-based materials through several possible mechanisms, including nano-filling, nucleation of hydration products, crack bridging or arresting, modification of pore structure, and improvement of interfacial characteristics. Nevertheless, these mechanisms are highly sensitive to GO dosage, sheet characteristics, dispersion technique, mixing energy, chemical admixtures, water-to-binder ratio, and curing conditions. Consequently, contradictory or inconsistent results among studies should not automatically be interpreted as evidence that GO is ineffective; differences in dispersion and mixture conditions may be responsible for a significant portion of the observed variation.

2.3 Graphene Oxide and Silica Fume in Combined Cementitious Systems

The combination of SF and GO provides an important example of multi-scale modification because the two materials influence cementitious systems through different but potentially complementary mechanisms. SF primarily contributes through particle packing and pozzolanic reaction, whereas GO can influence hydration, nano-scale pore structure, crack development, and interfacial characteristics.

Abdullah et al. (2021) experimentally investigated the combined use of GO and SF in cement-based composites using different proportions of the two materials. Their results demonstrated that appropriate proportions of GO and SF could enhance mechanical performance and that the relationship between the two material contents was not simply additive. The authors identified a composite interaction between SF and GO and proposed an approach for determining suitable proportions while maintaining effective GO dispersion.

An additional study investigating GO in concrete containing SF and manufactured sand reported that the presence of both SF and GO affected workability and required attention to dispersion and superplasticizer dosage. The study also reported that adequate dispersion of GO could be achieved in the presence of SF and an appropriate polycarboxylate-based superplasticizer. Microstructural observations indicated the development of a denser hydration-product structure. These findings are particularly relevant because they demonstrate that SF may influence not only the hardened matrix but also the dispersion behavior of GO.

Earlier research on the incorporation of GO and SF into cement paste also demonstrated that calcium ions in the cementitious environment can cause significant GO aggregation, while vigorous mixing can break larger aggregates into smaller agglomerates. The addition of the SF was reported to improve the dispersion of the GO nanosheets. This observation is important because it suggests that SF and GO may interact at the processing stage as well as at the hardened-matrix stage.

The combined literature therefore indicates that SF and GO should not be treated simply as two independent additives. SF may contribute to matrix densification and can influence the dispersion environment of GO, while GO may introduce additional nano-scale effects. At the same time, simultaneous incorporation of two fine materials can increase water demand and complicate workability control. The optimum combination is consequently expected to depend on the characteristics of both materials and on the overall mixture design.

2.4 Titanium Dioxide in Cement-Based Materials

Titanium dioxide (TiO_2) represents a different category of cement modification because its principal attraction is its photocatalytic functionality. TiO_2 can generate reactive species under suitable light irradiation, allowing it to participate in the degradation or transformation of selected pollutants and organic compounds. This has led to the development of photocatalytic cementitious materials for applications including self-cleaning surfaces, air-pollution mitigation, and functional infrastructure.

Hamidi and Aslani (2019) provided a comprehensive review of TiO_2-based photocatalytic cementitious composites and discussed the material characteristics, photocatalytic mechanisms, influencing parameters, and assessment methods. The review identified TiO_2 as one of the most widely investigated photocatalysts for cement-based applications because of its chemical stability and established photocatalytic activity. However, the authors

also emphasized that photocatalytic performance depends on factors such as TiO_2 characteristics, concentration, dispersion, surface accessibility, and the characteristics of the cementitious matrix.

Folli et al. (2012) investigated TiO_2 photocatalysis in cementitious systems with particular emphasis on self-cleaning and pollutant degradation. Their work considered both micro- and nano-sized TiO_2 in cement and mortar specimens and examined reactions associated with organic dye degradation and nitrogen oxide oxidation. Importantly, the study demonstrated that TiO_2 particle characteristics and their interaction with the cementitious environment are relevant to photocatalytic performance

The influence of the cementitious matrix and available active surface has also been demonstrated by **Jimenez-Relinque et al. (2015)**. Their experimental study examined the effects of binder type, surface roughness, and microstructure on the photocatalytic efficiency of TiO_2-modified cementitious materials. The results indicated that the available active surface was an important parameter controlling photocatalytic efficiency and that the composition and microstructure of the cementitious material could significantly affect photocatalytic performance.

Guo et al. (2017) investigated concrete surface layers containing nano-TiO_2 introduced through different incorporation approaches, including intermixed and spray-coated systems. Their results showed that experimental conditions such as ultraviolet-light intensity, relative humidity, pollutant concentration, and flow conditions could influence NOx conversion. This demonstrates that photocatalytic performance cannot be compared reliably between studies without considering the testing environment.

Similarly, **Guo and Poon (2018)** investigated the influence of cement type on TiO_2-based photocatalytic NOx removal. Their results demonstrated that cement composition can influence photocatalytic behavior, partly through differences in light absorption and interfacial charge-transfer characteristics. These findings validate the importance of considering the cementitious matrix when evaluating TiO_2 performance.

Yang et al. (2019) further investigated supported TiO_2 systems for photocatalytic concrete and reported that catalyst utilization efficiency and environmental conditions influence NOx-removal performance. The study also highlights the importance of catalyst loading and the durability of the photocatalyst at the concrete surface. Such findings are important for practical applications because laboratory photocatalytic performance does not necessarily translate directly into long-term field performance.

Recent reviews have further emphasized that the accessible active surface area is a critical factor for TiO_2-containing cementitious materials. As cement hydrates and surfaces undergo carbonation and other changes during service, the accessibility of TiO_2 particles may change, potentially affecting long-term photocatalytic performance. Therefore, the evaluation of TiO_2-modified concrete should consider not only the initial photocatalytic efficiency but also surface accessibility, environmental conditions, catalyst distribution, and long-term stability.

2.5 Comparative Analysis of Silica Fume, Graphene Oxide and Titanium Dioxide

The reviewed literature demonstrates that SF, GO, and TiO_2 modify conventional cement-based concrete through substantially different mechanisms. SF primarily functions as a supplementary cementitious material and contributes through pozzolanic reaction and particle-packing effects. Its major influence is therefore associated with matrix densification, pore refinement, and improvement of the cement paste and ITZ. GO, in contrast, is generally incorporated at much lower concentrations and acts as a nano-scale modifier. Its effects are associated with hydration, nano-filling, crack development, pore structure, and interfacial interactions. TiO_2 has a distinct functional role because its principal advantage is the introduction of photocatalytic activity in addition to possible microstructural and mechanical effects.

These differences mean that direct comparison based only on strength improvement is insufficient. SF may be particularly relevant where matrix densification and durability are primary objectives, whereas GO is potentially attractive for nano-scale modification and mechanical or microstructural enhancement. TiO_2 becomes particularly relevant when functional performance such as self-cleaning or pollutant degradation is required. Consequently, the appropriate material depends on the intended performance of the concrete.

The literature also demonstrates that the performance of all three materials is strongly dependent on dosage and distribution. For SF, increasing the content may increase particle-packing and pozzolanic benefits but may also increase water demand. For GO, very low dosages can be effective when dispersion is adequate, whereas excessive or poorly dispersed GO may form agglomerates and reduce its effectiveness. For TiO_2, increasing catalyst loading does not necessarily provide proportional photocatalytic improvement because the accessibility of active TiO_2 surfaces and mass transfer of reactants are important. Therefore, optimum dosage should be considered as a system-dependent parameter rather than as a universal material property.

Another important distinction is the relationship between conventional and functional performance. SF and GO are primarily investigated for their effects on mechanical and microstructural properties, although they may also influence transport and durability. TiO_2 introduces a different performance dimension through photocatalysis. Consequently, an integrated evaluation should consider whether modifications intended to densify the matrix or improve strength could unintentionally reduce the accessibility of TiO_2 particles required for photocatalytic reactions.

2.6 Fresh Properties, Dispersion and Workability

Fresh-state behavior is an important but comparatively underemphasized aspect of multi-material concrete. SF, GO, and TiO_2 all possess fine particle characteristics that can influence water demand and rheology, although their effects occur at different scales.

SF increases water demand by increasing the surface area of binder system. Experimental work on SF-containing concrete has shown that changes in rheology and workability can influence compaction and ultimately the hardened properties. In pervious concrete, for example, **Adil et al. (2020)** demonstrated that changes in paste rheology and void content were closely related to the resulting strength and durability.

GO introduces an additional dispersion challenge because its nanosheets have a strong tendency to interact with calcium ions in cementitious environments. Studies have demonstrated that sonication, high-shear mixing, and appropriate chemical dispersants can improve GO dispersion. However, the optimum dispersion procedure depends on the GO characteristics and cement system.

TiO_2 can also agglomerate, particularly when nano-sized particles are used in the highly alkaline and calcium-rich cement environment. **Hamidi and Aslani (2019)** discussed the tendency of TiO_2 particles to form agglomerates and emphasized the importance of particle size and dispersion. Therefore, simultaneous incorporation of SF, GO, and TiO_2 could produce a complex rheological and dispersion environment in which the total fine-particle surface area, chemical interactions, and admixture demand become important.

This indicates that workability should not be considered merely as a secondary property. In a multi-material system, poor fresh-state dispersion can directly affect the microstructure and therefore the mechanical, durability, and photocatalytic performance of the hardened concrete.

2.7 Mechanical Performance and Microstructural Modification

The mechanical response of SF-, GO-, and TiO_2-modified concrete is closely related to changes in hydration and microstructure. SF can improve strength through pozzolanic reaction, particle packing, and refinement of pores and the ITZ. GO can contribute through nano-filling, modification of hydration products, and interaction with the cement matrix. Experimental evidence has shown that appropriately dispersed GO can increase strength at low dosages, while excessive or poorly dispersed GO may reduce the expected benefits.

The combination of GO and SF provides an example of the importance of multi-scale interactions. SF can improve matrix density and may assist in the dispersion of GO, while GO can influence the morphology and distribution of hydration products. However, these effects depend on mixture proportions and processing conditions. Therefore, mechanical performance in a multi-material system should be interpreted together with microstructural evidence rather than solely from compressive-strength results.

TiO_2 may also influence mechanical properties, but its role is generally less direct than that of SF and GO. The incorporation of TiO_2 can alter particle packing and microstructure, but the primary reason for its use is often photocatalytic functionality. Consequently, the assessment of TiO_2-containing concrete should avoid treating mechanical strength as the only performance criterion.

Microstructural techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and pore-structure analysis can provide important evidence for explaining observed changes in mechanical and durability performance. A critical review should therefore consider whether reported macroscopic improvements are supported by corresponding microstructural evidence.

2.8 Durability and Transport Properties

Durability is strongly influenced by pore structure and the connectivity of transport pathways within cement-based materials. SF has a well-established role in reducing permeability and refining pore structure, with reviews reporting improvements in resistance to chloride transport, corrosion-related deterioration, sulfate attack, and other durability mechanisms. GO has also been associated with changes in pore structure and transport properties, although the magnitude of improvement varies with dosage and dispersion.

The interaction between strength and transport properties is particularly important. A denser cementitious matrix may simultaneously increase

compressive strength and reduce the penetration of water or aggressive ions. However, the same densification may affect surface characteristics that are important for photocatalytic applications. Therefore, a multi-material system should not be evaluated solely according to whether its pore structure is "denser" or "less permeable"; the required pore structure may differ depending on the intended application.

For TiO_2-containing concrete, durability also includes retention of photocatalytic functionality. A photocatalytic surface must retain sufficient accessible TiO_2 and maintain adequate contact between the catalyst, light, moisture, and pollutants. Surface carbonation, hydration, abrasion, weathering, and deposition of contaminants can therefore affect long-term functionality. This creates an important distinction between conventional durability and functional durability.

2.9 Multi-Material Modification and Potential SF–GO–TiO_2 Interactions

The available literature provides evidence for individual SF-, GO-, and TiO_2-based systems and for certain binary combinations, particularly SF + GO. However, the mechanisms identified for individual materials cannot automatically be assumed to remain unchanged when three materials are simultaneously incorporated into one cementitious system.

A potential SF–GO–TiO_2 system involves at least three different mechanisms. SF may promote matrix densification and pore refinement; GO may influence hydration, nano-scale structure, crack development, and interfacial bonding; and TiO_2 may provide photocatalytic functionality. In principle, these functions could be complementary. However, simultaneous incorporation may also introduce competing effects.

First, the combined fine-particle content may increase water demand and affect workability. Second, GO and TiO_2 may both require effective dispersion to achieve their intended functions. Third, SF-induced matrix densification could alter the accessibility of TiO_2 particles at the surface. Fourth, interactions among the materials, cement hydration products, and chemical admixtures may alter the microstructure in ways that cannot be predicted from individual-material studies.

Therefore, the concept of synergy should be treated as a hypothesis requiring experimental verification rather than as an established result. The available evidence supports the need for systematic investigation of the interaction between material dosage, dispersion, hydration, pore structure, mechanical performance, durability, and photocatalytic activity.

2.10 Research Gap

The reviewed literature demonstrates that the individual behavior of SF, GO, and TiO_2 in cement-based materials has been investigated extensively. SF has a well-established research base concerning strength, permeability, durability, and microstructural refinement. GO research has increasingly addressed mechanical performance, hydration, dispersion, transport properties, and microstructural modification. TiO_2 research has developed substantially around photocatalytic functionality, self-cleaning behavior, pollutant degradation, and the influence of cementitious surface characteristics.

However, important gaps remain in the integration of these research areas. First, the literature is not sufficiently unified with respect to the simultaneous consideration of mechanical, durability, microstructural, and photocatalytic performance. Second, the effects of dosage and dispersion are often investigated independently rather than as interacting parameters. Third, the available evidence concerning multi-material systems is substantially more developed for certain binary combinations, such as SF + GO, than for a three-material SF–GO–TiO_2 system. Fourth, the effect of matrix densification on the accessibility and long-term activity of TiO_2 requires further investigation.

Future experimental studies should therefore investigate SF, GO, and TiO_2 using controlled mixture designs and consistent testing procedures. Particular attention should be given to optimum proportions, dispersion methods, fresh-state properties, hydration behavior, mechanical performance, pore structure, permeability, durability, and photocatalytic activity. Long-term exposure studies are also required to determine whether improvements observed under laboratory conditions can be maintained during service.

Accordingly, the principal research opportunity identified by this review is not simply the use of three advanced materials together, but the development of a systematic understanding of how supplementary cementitious modification, nano-scale modification, and photocatalytic functionality interact within a conventional cement-based concrete system.

3. REVIEW METHODOLOGY

3.1 Literature Search Strategy

A literature review was undertaken to examine the effects of silica fume (SF), graphene oxide (GO), and titanium dioxide (TiO_2) on the properties and performance of conventional cement-based concrete. The review focused on published research investigating the influence of these materials on fresh properties, mechanical performance, durability, microstructural characteristics, and functional

behaviour. Relevant literature was identified using combinations of keywords, including "silica fume concrete," "graphene oxide cement composites," "titanium dioxide photocatalytic concrete," "graphene oxide and silica fume," and "multifunctional cementitious materials." Additional searches focused on hydration mechanisms, particle dispersion, pore structure, strength development, transport properties, and photocatalytic activity. Reference lists of relevant research articles and review papers were also considered to identify further studies related to the objectives of this review.

3.2 Selection and Classification of Literature

The collected literature was examined to identify studies relevant to the individual and combined incorporation of SF, GO, and TiO_2 into cement-based materials. Priority was given to peer-reviewed experimental investigations and review articles that provided information on material characteristics, incorporation methods, mixture proportions, testing procedures, or reported performance. Studies addressing cement paste, mortar, and conventional concrete were considered where their findings were relevant to understanding the behaviour of the selected materials in cementitious systems.

The selected literature was organized into five categories: SF-modified cementitious materials, GO-modified cementitious materials, TiO_2-modified cementitious materials, binary combinations of these materials, and potential interactions in multi-material systems. This classification enabled the individual mechanisms of the three materials to be examined separately before comparing their potential complementary effects and limitations when used together.

3.3 Framework for Critical Evaluation

The selected studies were critically evaluated according to their reported findings, experimental conditions, and proposed mechanisms of material modification. For SF, particular attention was given to pozzolanic activity, particle packing, pore refinement, matrix densification, and the resulting effects on mechanical performance and durability. For GO, the evaluation focused on dosage, dispersion techniques, hydration behaviour, microstructural modification, interfacial characteristics, and mechanical performance. For TiO_2, emphasis was placed on particle characteristics, incorporation methods, surface accessibility, photocatalytic activity, and the influence of environmental and testing conditions on functional performance.

Differences in binder composition, water-to-binder ratio, material dosage, mixing procedures, curing conditions, and testing methods were considered when interpreting the findings of individual studies. This comparative approach was used to examine variations in reported results and to identify the factors that may contribute to differences in the performance of modified cementitious materials. Particular consideration was given to whether reported improvements in mechanical and durability-related properties were supported by microstructural observations or complementary experimental evidence.

3.4 Comparative Synthesis and Research Gap Identification

The findings from the reviewed literature were synthesized to compare the respective contributions of SF, GO, and TiO_2 to fresh properties, mechanical performance, durability, microstructural development, and functional behaviour. The analysis distinguished the established effects of individual materials from potential interactions associated with their combined incorporation. Studies involving binary combinations were examined to understand the extent to which the modification mechanisms of different materials may complement or influence one another.

The comparative assessment also considered possible limitations associated with increased water demand, inadequate particle dispersion, material agglomeration, changes in pore structure, and reduced accessibility of photocatalytically active surfaces. Particular attention was given to the availability of research investigating the simultaneous incorporation of SF, GO, and TiO_2 and to the limitations of comparing studies conducted under different experimental conditions. The findings were used to identify research gaps concerning multi-material interactions, dosage optimization, dispersion methods, long-term durability, and the relationship between mechanical performance and photocatalytic functionality. These gaps provide the basis for identifying future research priorities for multifunctional conventional concrete incorporating SF, GO, and TiO_2.

4. CONCLUSION

This review has critically examined the incorporation of silica fume (SF), graphene oxide (GO), and titanium dioxide (TiO_2) into conventional cement-based concrete, with particular emphasis on fresh properties, mechanical performance, durability, microstructural development, and functional behaviour. The reviewed literature indicates that these materials modify concrete through fundamentally different mechanisms. Silica fume primarily contributes through its fine particle size, filler effect, and pozzolanic activity, resulting in pore refinement, matrix densification, and potential improvements in mechanical and durability-related properties. Graphene oxide acts mainly as a nano-scale modifier capable of influencing hydration, pore structure, interfacial characteristics, and crack development, while titanium dioxide introduces a distinct functional dimension through photocatalytic activity in addition to its possible effects on selected

properties of the cementitious matrix. Thus, the three materials should not be considered equivalent modifiers, and their contributions need to be evaluated according to their individual mechanisms and intended functions.

A critical synthesis of the available literature shows that the performance of SF, GO, and TiO_2 is highly dependent on material dosage, dispersion, mixture composition, and testing conditions. The beneficial effects reported for silica fumes are generally associated with suitable incorporation levels, whereas excessive fine-material content can increase water demand and adversely affect workability. For GO, dispersion is particularly important because agglomeration can reduce the effective surface area and limit its interaction with the cementitious system. Similarly, the photocatalytic effectiveness of TiO_2 depends not only on its quantity but also on its distribution, surface accessibility, particle characteristics, and exposure to suitable light conditions. Consequently, the literature does not support a simple relationship in which increasing the dosage of any one material continuously improves all concrete properties. Instead, performance is governed by the interaction between material characteristics, dosage, dispersion, mixture design, curing, and testing conditions.

The reviewed studies also demonstrate that improvements in one performance parameter may be accompanied by changes in other properties. Matrix densification produced by silica fume can contribute to strength development and reduced transport through the concrete, but increased fine-particle content may affect fresh-state behaviour. GO may contribute to microstructural refinement and mechanical performance when adequately dispersed, while poor dispersion can limit these benefits. TiO_2 can provide photocatalytic functionality, but its effectiveness is influenced by whether sufficient active surface remains accessible after incorporation into the cementitious matrix. These observations highlight an important consideration for multifunctional concrete: mechanical, durability, fresh-state, and functional properties cannot be optimized independently without considering their interactions.

The comparison of SF, GO, and TiO_2 indicates that their primary roles are complementary rather than identical. SF is principally associated with cementitious matrix refinement and improvements in strength and durability; GO provides nano-scale modification of hydration, pore structure, and interfacial characteristics; and TiO_2 provides photocatalytic functionality together with potential microstructural effects. This functional distinction provides a scientific basis for investigating their combined incorporation into conventional concrete. However, the available evidence does not justify assuming that the combined effects of SF, GO, and TiO_2 will automatically be additive or synergistic. The interaction among the materials may instead influence dispersion, workability, hydration, pore structure, interfacial characteristics, and TiO_2 surface accessibility. Therefore, the performance of a combined SF–GO–TiO_2 system must be established experimentally rather than inferred from the performance of the individual materials.

An important limitation identified in the existing literature is the lack of directly comparable studies conducted under a common mix-design and testing framework. Differences in cement type, water-to-binder ratio, supplementary materials, material characteristics, curing conditions, dispersion procedures, dosages, specimen preparation, and testing methods make direct comparison of reported results difficult. In particular, the literature on individual and binary material systems is considerably more developed than evidence addressing the simultaneous incorporation of SF, GO, and TiO_2. This limits the ability to establish reliable optimum proportions or to determine whether the interaction of the three materials provides a measurable advantage over individual or binary modifications.

Based on the reviewed evidence, several research priorities can therefore be identified. Future studies should systematically investigate the effects of SF, GO, and TiO_2 at controlled dosages and under consistent mix-design conditions. Particular attention should be given to GO dispersion, the distribution and accessibility of TiO_2, and the influence of SF on the overall particle packing and fresh-state behaviour of the mixture. Microstructural investigations using appropriate characterization techniques should be correlated with mechanical, durability, and photocatalytic results to establish the mechanisms responsible for observed changes. Long-term durability and retention of photocatalytic functionality should also be evaluated because improvements observed at early ages may not necessarily represent long-term field performance.

Future experimental research should further compare individual, binary, and ternary material systems rather than evaluating only a single combined mixture. Such an approach would allow the individual contribution of each modifier and any interaction effects to be distinguished more reliably. Workability, compressive and tensile strength, durability-related properties, pore structure, microstructure, and photocatalytic performance should be evaluated using consistent procedures. In addition, environmental impact, material cost, scalability, and practical mixing requirements should be incorporated into the assessment because laboratory-scale performance alone is insufficient to establish the practical suitability of multifunctional modified concrete.

Overall, the reviewed literature demonstrates that SF, GO, and TiO_2 provide three distinct approaches to modifying conventional cement-based concrete: matrix refinement and densification through SF, nano-scale modification through GO, and photocatalytic functionality through TiO_2.

Their different mechanisms create a potential basis for developing multifunctional concrete with simultaneously improved structural and functional characteristics. Nevertheless, the existing evidence indicates that such performance depends strongly on dosage, dispersion, material interaction, mixture composition, and exposure and testing conditions. The principal research challenge is therefore not simply to determine whether SF, GO, and TiO_2 can be incorporated together, but to establish under controlled conditions whether their combined use can provide a demonstrable and practically meaningful balance between fresh properties, mechanical performance, durability, microstructural development, and photocatalytic functionality. Systematic experimental and long-term investigations are required to establish this relationship and to determine the feasibility of SF–GO–TiO_2 modified conventional concrete for practical construction applications.

5. REFERENCES

[1] R. Siddique, "Utilization of silica fume in concrete: Review of hardened properties," Resources, Conservation and Recycling, vol. 55, no. 11, pp. 923–932, 2011.

[2] M. I. Khan and R. Siddique, "Utilization of silica fume in concrete: Review of durability properties," Resources, Conservation and Recycling, vol. 57, pp. 30–35, 2011.

[3] R. Siddique and N. Chahal, "Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar," Resources, Conservation and Recycling, vol. 55, no. 8, pp. 739–744, 2011.

[4] Y. Suo, R. Guo, H. Xia, Y. Yang, B. Zhou, and Z. Zhao, "A review of graphene oxide/cement composites: Performance, functionality, mechanisms, and prospects," Journal of Building Engineering, vol. 53, Art. no. 104502, 2022.

[5] A. Bagheri, E. Negahban, A. Asad, H. A. Abbasi, and S. M. Raza, "Graphene oxide-incorporated cementitious composites: A thorough investigation," Materials Advances, vol. 3, pp. 9040–9051, 2022.

[6] A. Abdullah, M. Taha, M. Rashwan, and M. Fahmy, "Efficient use of graphene oxide and silica fume in cement-based composites," Materials, vol. 14, no. 21, Art. no. 6541, 2021.

[7] A. Folli, C. Pade, T. B. Hansen, T. De Marco, and D. E. Macphee, "TiO_2 photocatalysis in cementitious systems: Insights into self-cleaning and depollution chemistry," Cement and Concrete Research, vol. 42, no. 3, pp. 539–548, 2012.

[8] L. Zhao et al., "An intensive review on the role of graphene oxide in cement-based materials," Construction and Building Materials, vol. 241, Art. no. 117939, 2020.

[9] G. Jing, Z. Ye, D. Qian, and Y. Li, "From graphene oxide to reduced graphene oxide: Enhanced hydration and compressive strength of cement composites," Construction and Building Materials, vol. 248, Art. no. 118699, 2020.

[10] H. Du and S. Chen, "Dispersion of graphene oxide and its application prospect in cement-based materials: A review," Journal of Dispersion Science and Technology, vol. 44, no. 3, pp. 392–405, 2023.

[11] R. Mowlaei et al., "The effects of graphene oxide-silica nanohybrids on the workability, hydration, and mechanical properties of Portland cement paste," Construction and Building Materials, vol. 266, Art. no. 121016, 2021.

[12] E. Jimenez-Relinque et al., "Characteristics and efficiency of photocatalytic cementitious materials: Type of binder, roughness and microstructure," Cement and Concrete Research, vol. 71, pp. 124–131, 2015.

[13] M. Guo, T.-C. Ling, and C.-S. Poon, "Photocatalytic NOx degradation of concrete surface layers intermixed and spray-coated with nano-TiO_2: Influence of experimental factors," Cement and Concrete Composites, vol. 83, pp. 279–289, 2017.

[14] M. Guo and C.-S. Poon, "Superior photocatalytic NOx removal of cementitious materials prepared with white cement over ordinary Portland cement and the underlying mechanisms," Cement and Concrete Composites, vol. 90, pp. 42–49, 2018.

[15] L. Yang et al., "Photocatalytic concrete for NOx abatement: Supported TiO_2 efficiencies and impacts," Cement and Concrete Research, vol. 116, pp. 57–64, 2019.

[16] W. Shen et al., "TiO_2 nanoparticle modified photocatalytic self-cleaning concrete," Journal of Cleaner Production, vol. 87, pp. 762–765, 2015.

[17] M. Adil et al., "Influence of silica fume on mechanical and durability of pervious concrete," Construction and Building Materials, vol. 247, Art. no. 118453, 2020.