

Utilization of Graphene as a Construction Material for Sustainable Buildings

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Abstract: Sustainability in construction has been an everlasting global goal to reduce the emission of greenhouse gases that have had detrimental effects on the environment and negatively impacted human life in general. Graphene, a two-dimensional material exhibiting exceptionally desirable properties, has shown great potential to impact the building and construction sectors significantly. Graphene and its derivatives can easily be used as an additive in concrete-based composites (CBC) to improve their mechanical and durability properties and their safety, with prospects of fostering sustainability. This paper uses a scoping and compressive thorough mixed review approach, and this research aims to assess the endeavors in utilizing Graphene and Its derivatives in cementitious composites and to chart the perspectives found in the existing literature. The paper selected 64 articles from a pool of 576 publications based on their relevance. The comprehensive review concludes that the benefit of using Graphene and its derivatives as a reinforcement in cement composites lies in its superior ability to improve mechanical properties, including tensile strength and compressive strength, and improves durability by restricting crack initiation and expansion at the nanoscale, and enhances resistance to chloride and sulphate attacks as well as improving the safety of concrete based composites, setting it apart from traditional reinforcement methods.

Keywords: Concrete Based Composites, Construction, Graphene, Mechanical Properties, Sustainability

1. Introduction

Sustainable buildings are one of the sustainable development goals of the United Nations towards a peaceful and safe planet for both the developed and developing nations, now and into the future (United Nations, 2023). It is essential to eliminate or reduce the pollution generated when establishing these sustainable structures, as it is among the sustainable development goals (Huang and Wu, 2021). The industrial process of producing cement has primarily contributed to the emission of CO₂ gas that has detrimental effects on the environment, posing health threats. It is, therefore, of great importance to invent ways of eliminating or reducing the generation of CO₂ gas (Huang and Wu, 2013). Therefore, this research studies the viability of Graphene as a possible solution for sustainability in construction.

Graphene is a nanostructure allotrope of carbon in a two-dimensional crystalline form existing as a single layer of carbon atoms in a hexagonal lattice or several coupled layers of a honeycomb structure (Britannica, 2023). Graphene and its derivatives have found a special



place in construction because of their enormous favorable properties, such as good physical and mechanical properties (Li et al., 2023), chemical resistance, and durability (Sun et al., 2021). The ability of Graphene to improve the strength of concrete for structures is highly desirable while reducing the bulkiness of concrete required. Graphene use will reduce construction costs by producing lighter structures and reducing the materials needed to achieve the same structural properties (Asim et al., 2022).

(Li et al., 2023) Graphene has desirable properties when mixed as an additive on cement-based materials. It improves the workability of concrete mechanical properties and enhances the concrete's performance in achieving the desired strength within the shortest period. An experiment to investigate concrete's compressive behaviour and durability using plastic waste and Graphene showed an increased compressive toughness and porosity. It also exhibited increased abrasiveness and corrosive resistance to chlorides and sulphites, hence improvement in the durability of concrete (Adamu et al., 2022). Graphene has also shown great promise in composite construction materials. Graphene reinforces these composites necessary for structural application (Zheng et al., 2017).

Graphene has stirred up tremendous interest in its application in sustainable buildings. Recent successful research on Graphene and its derivatives and their utilization with cementitious products have shown its excellent mechanical, physical, and thermal properties that have fostered increased concrete strength, workability, and durability (Han, Zhang and Ou, 2017). Therefore, this research tries to develop a more tailored graphene and its derivatives to produce an improved cementitious composite and ensure a high-performing multifunctional concrete.

This study focuses on establishing an optimum concrete design mix with Graphene and its derivatives that will yield concrete with maximum compressive strength, optimum tensile enhancement, desirable stiffness, and crack resistance while improving the durability of concrete while maintaining cost-effectiveness. The research also looks into the resistance of the resultant concrete mix against abrasive chemicals such as sulphites and chlorides for application in sewer structures.

2. Literature Review

Mechanical, Physical, and Thermal Properties of Graphene

Graphene is a recently discovered substance composed of carbon sheets resembling honeycombs and merely one atom in thickness (Woodford, 2012). Graphene is a strictly two-dimensional allotrope of carbon with remarkably high crystal and electronic quality levels. Despite its relatively brief existence, it has already unveiled a wealth of novel physics and possible uses (Geim and Novoselov, 2007).

Graphene has two leading derivatives, namely graphene oxide (GO), obtained through the oxidation of Graphene, and reduced graphene oxide (rGO), which can be synthesized by the reduction of GO (Magne et al., 2022). Graphene and its derivatives, however, exhibit highly similar structures that give rise to two-dimensional materials (Tahriri et al., 2019). The primary distinctions between GO and rGO include a higher prevalence of carboxyl groups, more significant defects, and reduced oxygen content in the latter form (Rout and Jena, 2021).

Graphene has numerous desirable properties, such as high electrical and thermal conductivity, good optical absorption of white light (Fuente, 2023), exceptional strength and stiffness, mechanical resilience, and water-repellent properties (Abergel et al., 2010). The more desirable properties of Graphene for construction applications are the mechanical, thermal, and durability properties that have stirred up more research. The ability of Graphene to bond with the cementitious product has shown great promise for its utilisation in the construction industry (Li et al., 2023).

Application of Graphene as a Construction Material

Graphene has found numerous industrial applications since its discovery. Graphene and its derivatives have been applied in nanotechnology, biomedical, bioelectrical, and energy sectors (Geim and Novoselov, 2007), (Schwierz, 2010), (Li et al., 2019) and (Choi et al., 2013). Recent studies have shown great promise for Graphene application construction (Li et al., 2023). Graphene was successfully used to reinforce asphalt roads to increase strength and durability, reducing the maintenance cost of these roads (Jyothirmai, Kiranmai and Vagdevi, 2020). Guo et al. (2022) found recommendable improvement in road performance when Graphene and its derivative were applied to the asphalt.

Additionally, the thermal storage stability of the asphalt binder improved its resistance to permanent deformation. Asim et al. (2022), in their intensive study of the application of Graphene to the construction industry for sustainable infrastructure, observed that some industries are using Graphene in their cementitious composite to produce a sustainable product that has improved mechanical and durability properties while reducing the carbon print. They also asserted that Graphene can be used in any construction, such as roads, industrial plants, bridges, and tunnels.

Evaluation of Safety of Graphene

Graphene is a revolutionary material with great potential for technological advances. Therefore, it is important to assess its safety profile regarding human health, environmental safety, and fire hazards (Bianco, 2013). Adopting Graphene by many industries will increase human exposure to the material, intentionally or unintentionally (Bussy, Ali-Boucetta and Kostarelos, 2013). Therefore, studying the effect of such exposure is necessary to mitigate the hazardous health effects that may arise (Fadeel et al., 2018). Graphene can pose potential risks to human health depending on how they are manufactured and processed. They can be released into the environment through various mechanisms, such as wear and abrasion of the end product. These materials can lead to skin issues, inflammation, genetic mutations, interstitial fibrosis, lung tumours, and vascular problems (Sousa et al., 2020) (Bianco and Prato, 2015).

Potential emission of toxicity to the environment by Graphene and its derivatives majorly occurs during the production stage (Serrano-Luján et al., 2019). Therefore, more studies to ensure sustainable production of this viable material have been put in place, and some success has been recorded, and industries are already adopting it for effective and safe production (Park et al., 2017). Nanomaterials, including Graphene, have been used to enhance the fire safety of polymer composites by combining barrier capabilities and catalytic properties and promoting carbonization effects (Cai et al., 2021). Graphene and its derivatives promote higher fire safety by forming tightly connected network barriers that slow the transfer of heat and substances



between the combustion area and the underlying construction material with any polystyrene matrix (Shi et al., 2019). Therefore, Graphene can be utilised in the construction sector to enhance the fire resistance of the sustainable structure (Wang et al., 2018).

3. Methodology

This paper conducts a scoping review of research on applying Graphene and its derivatives in constructing sustainable buildings. This paper primarily focuses on the most crucial direction among the six directions identified in the literature review due to the abundance of available papers in this cluster.

Scoping Review

The scoping review technique was preferred for this study rather than a systematic review (Nightingale, 2009) (Snyder, 2019). A scoping review is a valuable strategy to focus on the breadth of literature coverage regarding a specific topic (Munn et al., 2018). This aligns with the objectives of the study, which are to establish the optimum mix with Graphene that will produce the optimum desired properties for its application in the construction of sustainable buildings (Rumrill, Fitzgerald and Merchant, 2010).

Data Extraction

The literature was searched through the Worldwide Science database in the first step. The following combination of keywords (Graphene AND (Cement) AND Concrete) was used in the second step to search for the relevant literature. In the next step, to decide the eligibility of the detected papers for inclusion, search refinement was conducted considering several criteria:

- 1) Peer-reviewed journal papers,
- 2) papers in English,
- 3) and papers related to the construction phase.

In this step, duplicated papers were eliminated. In the last step, titles and abstract screenings were carried out to have the desired papers requiring intensive review and analysis. Figure 1 below summarizes the steps adopted in data extraction and analysis (Farahzadi and Kioumars, 2022).



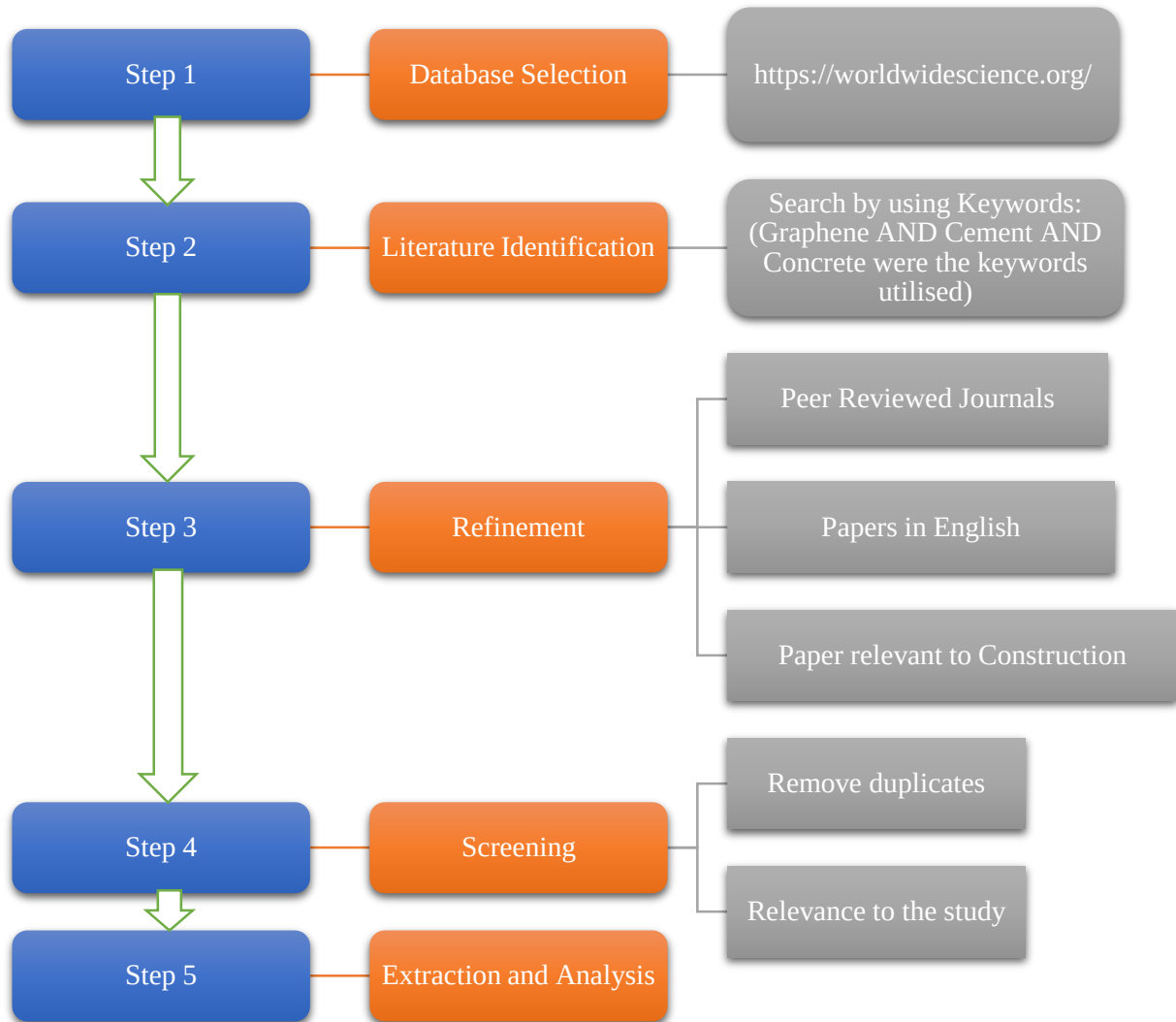


Figure 1: Literature Review Methodology

4. Results

Paper Selection and Analysis

The paper search was done by searching for relevant papers from the worldwide science database, and as a result, 576 papers were identified. After carrying out the first initial screening, 174 papers remained. After removing the duplicates and papers not in English and screening paper titles and abstracts, the number of relevant papers for this literature was reduced to 98 papers that were retained for scoping review. Since this study focuses on sustainable buildings, 64 out of 98 papers were reviewed holistically.

Content Analysis of Reviewed Papers

The identified papers were categorized into three clusters

- 1) Enhancement of mechanical properties
- 2) Improved durability
- 3) Improved safety

Enhancement of mechanical properties

The mechanical properties of key interest for structural application are compressive strength, tensile strength, flexural strength and shrinkage (Popov, 1998). Bheel et al. (2023) investigated GO with concrete to study mechanical properties including compressive strength, direct tensile strength, tensile capacity, flexural strength, modulus of elasticity, Poisson's ratio, and drying shrinkage. Thirteen mixtures comprising different blends were created: GO concentrations at 0.05%, 0.065%, and 0.08%, along with PVA (polyvinyl alcohol) concentrations at 1%, 1.5%, and 2%. The highest enhancements observed were as follows: a 30% boost in compressive strength, a 35% increase in direct tensile strength, a 49% improvement in flexural strength, and a 33.9% elevation in modulus of elasticity when incorporating 0.05% GO into the mixes.

While investigating the effect of Graphene on cementitious products, (Wang, Yang and Ouyang, 2019), found that at a dosage of 0.03% by weight of cement for GO nanosheets. The GO dosage applied by weight was 0.00%, 0.01%, 0.03%, and 0.05%. At optimum GO dosage, there was a 21.37% rise in compressive strength, a 39.62% increase in flexural strength, and a 53.77% boost in tensile strength after 28 days.

A study carried out by Du et al. (2019) to determine the abrasion resistance of Ordinary Portland Cement (OPC) when admixed with graphene oxide revealed that an optimum increase in compressive strength was achieved with the mix of 0.1% of GO by weight. Four different dosages of 0, 0.01, 0.05, and 0.1% of GO were applied, which yielded an increase of compressive strength from 54.2 MPa to 57.9 MPa, 56.6 MPa, and 84.5 MPa with an improvement of 6.8%, 4.5%, and 55.8%, respectively. It was also observed that the abrasive resistance of the OPC admix with GO increased due to an increase in compressive strength and a great reduction of mass loss of OPC.

Compared to compressive strength, higher flexural strength is normally achieved when GO is utilized in concrete. Lu and Ouyang, (2017) experimented with GO dosages of 0.00%, 0.01%, 0.03%, 0.05%, 0.08%, and 0.10% by weight of cement (bwoc), and concluded that mechanical properties were significantly enhanced. An increase of 21.1% and 15.5% was exhibited for flexural and compressive strength at three days.

While utilizing silica and Graphene, Salah et al., (2023) developed a ultra-high performance mortar with silica fumes (SF) and injecting graphene nanoplates dosages of 0%, 0.5%, 1%, 1.5% and 2% by weight of cement. A significant increase the mechanical properties investigated was observed when 1.5% (bwoc) of graphene nanoplates and 20% of SF were utilized. The compressive strength (CS) increased from 70.7 MPa to 133.3 MPa after 28 days. Additionally, the flexural strength (FS) and tensile strength (TS) reached 20.66 MPa and 14.67 MPa, respectively, in contrast to the control blend, which had values of 9.75 MPa for FS and 6.36 MPa for TS.

Ismail et al. (2022) experimented with 0.00%, 0.02%, 0.05%, 0.10%, 0.30%, and 0.50% wt of cement dosage of graphene nanoplates on the mechanical properties of concrete. They observed



a significant enhancement of mechanical properties when the optimum dosage of Graphene nanoplate of 0.02% was used. An increase of 20.82% and 30.05% for compressive strength and flexural strength, respectively, was recorded. Furthermore, including 0.02% Graphene Nanoplates resulted in a 36% increase in cracking load, a 23% increase in yield load, and a 15% increase in ultimate load for the beams.

Hong et al. (2023) utilized GO dosages 0.02%, 0.04%, 0.05%, 0.06%, and 0.08% (by cement weight) when conducting experiments on six samples. Their experimental findings demonstrated that the ideal quantity of 0.05% GO can achieve a 20.1% increase in compressive strength, a 34.3% increase in flexural strength, and a 24.2% increase in splitting tensile strength.

The findings by Lv et al. (2013) revealed that GO nanosheets played a role in facilitating the formation of hydrate crystals with a flower-like structure, leading to a significant improvement in the tensile, flexural, and compressive strengths of cement composites. Notably, when the GO content was 0.03%, the cement composites exhibited a remarkable increase in their tensile strength by 78.6%, flexural strength by 60.7%, and compressive strength by 38.9% when compared to composites without the inclusion of GO.

The summary of the studies carried out on Graphene and its derivatives is shown in Table 1 below.



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Table 1: Summary of studies carried out on Graphene and its derivatives

Paper Title	Mixes Applied (%)	Optimum mix (%)	Optimum Results Obtained	Reference
“Effects of Graphene Oxide on the Properties of Engineered Cementitious Composites: Multi-Objective Optimization Technique Using RSM”	13 Mixes (Combo) GO 0.05%, 0.065% & 0.08% PVA 1.0%, 1.5% & 2.0%	0.05% GO and 1% PVA	30% - compressive strength 35% - direct tensile strength 49% - flexural strength 33.9% - modulus of elasticity	(Bheel et al., 2023)
“Effect of Graphene Oxide on Mechanical Properties of Cement Mortar and its Strengthening Mechanism”	4 Mixes GO 0%, 0.01%, 0.03% & 0.05%	0.03% GO	21.37% - compressive strength 53.77% - tensile strength 39.62% - flexural strength	(Wang, Yang and Ouyang, 2019)
“Effect of admixing graphene oxide on abrasion resistance of ordinary Portland cement concrete”	4 Mixes GO 0%, 0.01%, 0.05% & 0.1%	0.1% GO	55.8% - compressive strength Improved abrasive resistance	(Du et al., 2019)
“Properties of Cement Mortar and Ultra-High Strength Concrete Incorporating Graphene Oxide Nanosheets”	6 Mixes GO 0%, 0.01%, 0.03%, 0.05%, 0.08 & 0.1%	0.05% GO	15.5% - compressive strength 21.1% - flexural strength	(Lu and Ouyang, 2017)
“Development of Ultra-High-Performance Silica Fume-Based Mortar Incorporating Graphene Nanoplatelets for 3-Dimensional Concrete Printing Application”	15 Mixes (Combo) Graphene 0%, 0.05%, 0.1%, 1.5%, 2%, Silica Fumes 0%, 10% & 20%	1.5% graphene and 20% Silica Fume	88.54% - compressive strength 130.6% - tensile strength 111.1% - flexural strength	(Salah et al., 2023)

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Paper Title	Mixes Applied (%)	Optimum mix (%)	Optimum Results Obtained	Reference
“Behavioral assessment of graphene nanoplatelets reinforced concrete beams by experimental, statistical, and analytical methods.”	6 Mixes Graphene Nanoplates 0%, 0.02%, 0.05%, 0.10%, 0.30%, and 0.50%	0.02% Graphene Nanoplates	20.82% - compressive strength 30.05% - flexural strength Beams 36% - cracking load 23% - yield load 15% - ultimate load	(Ismail et al., 2022)
“Effect of Graphene Oxide on the Mechanical Properties and Durability of High-Strength Lightweight Concrete Containing Shale Ceramsite”	6 Mixes GO 0%, 0.02%, 0.04%, 0.05%, 0.06 & 0.08%	0.05% GO	20.1%-compressive strength 34.3% - flexural strength 24.2%-splitting tensile strength	(Hong et al., 2023)
“Effect of Graphene Oxide nanosheets of microstructure and mechanical properties of cement composites”	6 Mixes GO 0%, 0.01%, 0.02%, 0.03%, 0.04 & 0.05%	0.03% GO	38.9%-compressive strength 60.7% - flexural strength 78.6% - tensile strength	(Lv et al, 2013)

Improved Durability of Concrete Structures

Chintalapudi and Pannem (2022) investigated the effect of sulphuric acid on OPC and PPC concrete reinforced with GO. The specimen was exposed to sulphuric acid with a concentration of 5% with distilled water. PPC concrete type was adversely affected as compared to OPC concrete. Generally, a significant improvement in resistance against sulphuric acid was observed on concrete reinforced with Graphene compared to the one that was only plain concrete.

(Hong et al., 2023) investigated the effect of the GO on the concrete ability to resist chloride penetration, sulphate attack, and effects of freezing and thaw. At GO concentration of 0.05%, chloride penetration resistance increased by 43%, and Mass loss due to sulphite attack and freeze and thaw attacks was 1.54% and 1.10%, respectively.

Upon analyzing the microstructure and properties of the nanocomposite coating, it was evident that introducing a moderate quantity of GO significantly enhances the epoxy coating's impermeability. The nanocomposite coating containing 0.3 wt.% of GO exhibited the highest resistance to chloride ion infiltration because of the even distribution and chemical bonding of GO within the epoxy coating (Zheng et al., 2020).

Improved Safety

Shi et al. (2018) investigated the effects of GO on the enhancement of fire safety for sustainable structures. In their evaluation of the combustion behaviour, they observed a 31% decrease in the highest heat release rate and a 34.3% decrease in the overall heat release.

Under extreme temperatures (above 200⁰ C), concrete destructive expansion occurs that may lead to severe cracking that compromises the structural integrity of the building. Graphene-based concrete has greater potential for damage-sensing applications that will enhance safety in general (Papanikolaou, Al-Tabbaa and Goisis, 2019).

5. Discussion

The study focused on incorporating GO in concrete to evaluate the resultant mechanical and durability features encompassing compressive strength, flexural strength, tensile strength, modulus of elasticity, resistance to abrasion, and chloride ion concentration. After a thorough analysis of 34 journals, the findings suggest that more than 40% of these publications emphasize that incorporating GO at levels of 0.03% and 0.05% of the cement's weight yields the most substantial improvement in the mechanical strength of cement-based composites. However, if the dosage surpasses this range, there is a decline in mechanical strength.

The excessive presence of GO could not effectively disperse within the concrete due to an elevated calcium concentration, leading to a decrease in compressive strength (Xu and Fan, 2020). Incorporating GO at a dosage of 0.10% leads to a significant enhancement in abrasion resistance and a substantial reduction in the mass loss of OPC concrete (Du et al., 2019). The addition of 0.06% resulted in a substantial 60% reduction in chloride ion concentration. When chloride ions interact with reinforcing steel, they disrupt the passivation layer, initiating corrosion. This expansion is primarily induced by the elevated levels of free calcium oxide (CaO) and anhydrous sulfuric acid (SO₃). The rapid expansion occurs as sulfuric acid anhydrite



reacts with cement containing tricalcium aluminate in the presence of water. Consequently, lower chloride ion concentrations contribute to increased concrete durability (Zheng et al., 2020).

Nanomaterials pose no hazard when securely incorporated within a solid, structurally stable medium like concrete. The potential risk emerges solely if workers are exposed to nanomaterials in dust or aerosols (Papanikolaou, Al-Tabbaa and Goisis, 2019).

The concrete-based composites induced with Graphene and its derivatives exhibited the highest thermal stability with the temperature at maximum decomposition rate increasing by 15⁰ C and higher char residue (Shi et al., 2019). It provides suitable barriers to protect the underlying polymers and inhibits the heat and mass exchange between the gas and solid phases (Shi et al., 2018).

6. Conclusion

A comprehensive literature review, including journals obtained from a worldwide science database, was conducted to explore the outcomes of incorporating Graphene and its derivatives into cement-based composites. Graphene Oxide is the most utilised derivative of Graphene that has gained significant attention, and its use in concrete-based composites (CBCs) demonstrated exemplary results over time.

The studies unveiled that adding 0.03% GO content can significantly enhance compressive, flexural, and split tensile strength, with improvements ranging from 15% to 25%. Notably, GO exhibited favorable effects on the chemical properties of these composites. The introduction of 0.05% GO reduced weight loss under acidic conditions and decreased expansion due to sulfate attack by 70% and 20%, respectively, enhancing the performance of Concrete Based Composite.

It is important to note that adding GO has enhanced cementitious composites' properties. Nevertheless, further research is necessary in this field to optimize the utilization of GO for more significant results.

7. Recommendations

It's important to note that while graphene oxide holds great promise for the construction industry's sustainability, there are challenges related to cost, scalability, and potential health and safety concerns that must be addressed. Additionally, more research and development are required to fully harness the potential of Graphene and its derivatives in construction while ensuring its benefits are realized without causing unintended negative consequences.

8. Implications of the paper

This paper on Graphene and its derivatives in the construction industry can have several implications and research directions towards sustainability development, such as performance optimization aiming to maximize their sustainability benefits while minimizing costs and potential environmental impacts, scaling up production of graphene oxide for construction materials, addressing issues related to cost, availability, and feasibility on a larger scale, and investigating potential health and safety concerns related to the production and use of graphene



oxide in construction materials, and after that, develop safety guidelines and protocols for workers and end-users.

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