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# ADVANCES IN SUSTAINABLE CONCRETE THROUGH INDUSTRIAL WASTE UTILIZATION AND NANOTECHNOLOGY

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## Abstract

*Concrete is the building industry's most widely used commodity that is blamed for some of the pollution issues around the world. So by replacing concrete ingredients, it can theoretically conserve natural resources and production of cement, reduce energy consumption, and remove small landfill areas of excessive waste production. Therefore, this research focuses on the behavior of industrial solid waste materials (waste glass powder, waste marble powder, silica fumes, fly ash, E-waste, blast furnace slag , pumic and nano materials ) as replacement of concrete ingredients. It not only resolve the problem of landfill but also enhances the concrete properties. Green concrete manufacturing can be improved by using nanotechnology as it studies the behavior of material at atomic scale $10^{9}$. The methodology involves a comprehensive analysis of life cycle assessment studies, country-specific waste material production, and concrete performance focusing on environmental impacts and physical properties. This review is beneficial for construction industry and researchers to identify new material for sustainable construction.*

## INTRODUCTION

Due to factors like the partial substitution of waste items for cement, the avoidance of waste disposal expenditures, the reduction of production energy consumption, and the increased durability, green or sustainable concrete is frequently also less expensive to create. Green concrete is a type of concrete that looks like regular concrete but uses less energy and has less of an adverse environmental impact during manufacturing or use. For every tonne of concrete produced, the CO2 emissions associated with this process range from 0.1 to 0.22 tons [1, 34]. When clays and limestone are crushed and heated to high temperatures, the greenhouse gas is emitted [2, 35].

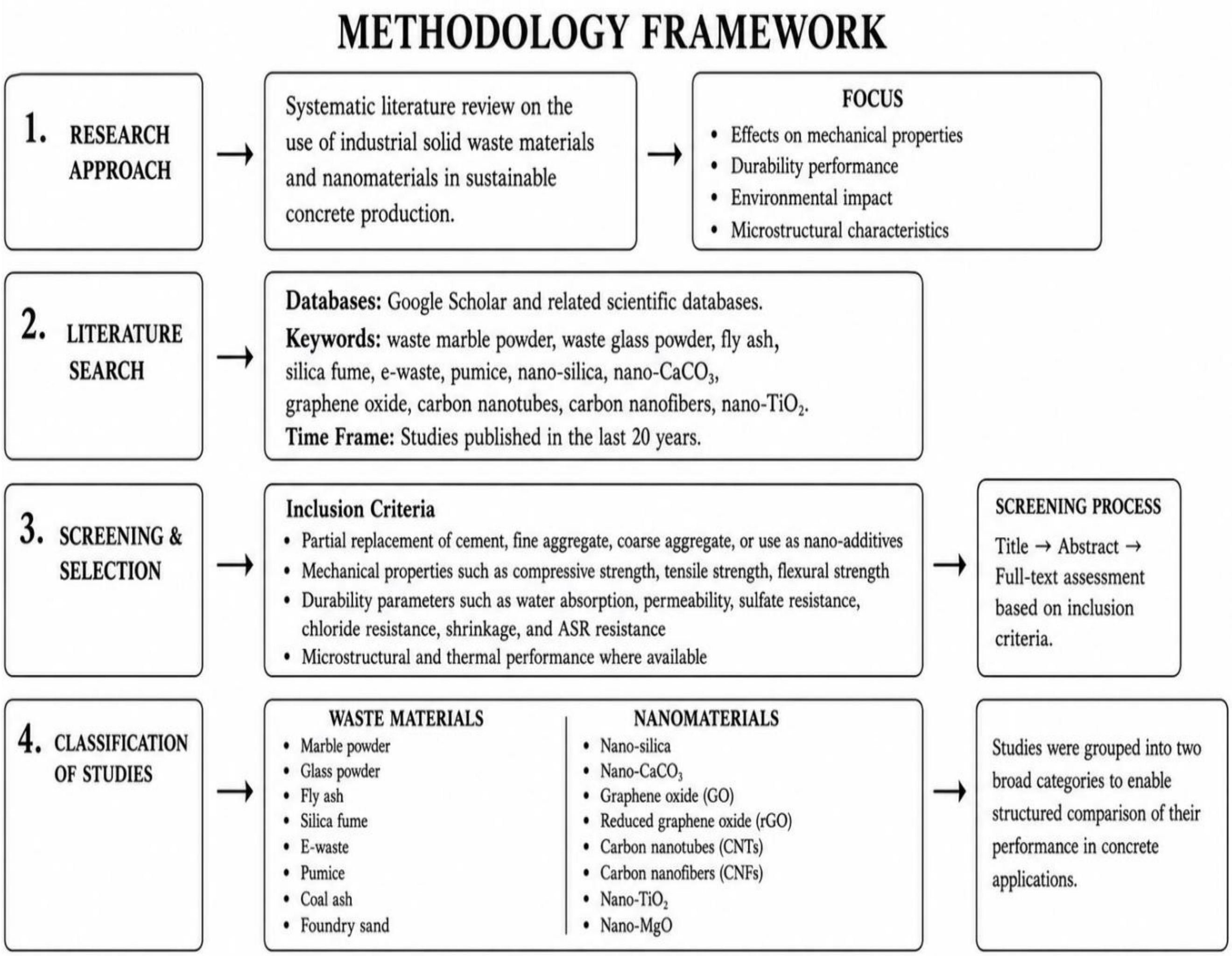
Waste usage is preferable to disposal since it reduces or even eliminates disposal expenses and related environmental problems while conserving resources. From a variety of angles, such as the conservation and recycling of energy in manufacturing processes, the preservation and sustainability of nonrenewable natural resources, and the mitigation of pollution, trash reuse is essential [3,4]. Many types of "green concrete" are being created in response to the increasing demand to lessen the negative effects of the building sector, conserve raw materials, and avoid the disposal of industrial waste [4, 49].The waste products from industry, agriculture, bio-waste, marine debris, and e-waste can all be recycled and utilized as additional components for Green Concrete. This will lessen the energy usage and environmental impact of OPC production. Both now and in the future, nanotechnology will play a huge role in green building applications. Green Concrete's development and application are still in their early phases [5, 38].

The manufacture of nanomaterials is still done on a lab scale, tends to be very energy intensive, and is not fully optimized. Although the use of nanomaterials in concrete is growing, there are still few studies on their effects on the environment or their possible ecotoxicity and toxicity (for example, from a safe and sustainable-by-design perspective) and further research is needed [6, 39]. Concrete is currently utilizing nanotechnology. By increasing the materials' lifespan, both organic and inorganic species can be employed as nano agents to create materials with better qualities, resulting in financial and environmental benefits [7, 47].

An enormous amount of waste materials from different surroundings, environments and industries are produced every day. The waste materials such as rice husk ash (RHA), saw dust ash (SDA), rubber crump, plastic waste, coconut husk and shell, textile waste (sludge and fiber) etc lead to waste disposal crisis. Recycle of such types of wastes can be used as an admixture to make the Green Concrete structures. This will reduce the quantity of cement used and $CO_2$ emission and reduce the global warming. In this paper, the explanation is about the waste materials as an admixture which provides better strength and durability of concrete than the existing one which not only solves the environmental and ecological problems but also significantly improves the microstructures and durability properties of concrete. So this study summarizes the waste materials and nano materials along with its properties.

## Methodology

Current research about green concrete and nanotechnology in concrete was studied to gather the necessary information that any unknowledgeable reader would need to comprehend the article. This study was conducted as a systematic literature review on the use of industrial solid waste materials in sustainable concrete production. The review focused on identifying the effects of different waste-based additives and nano-additives on the mechanical, durability, environmental, and microstructural properties of concrete. Below is the framework as figure 1.



Systematic literature review on the use of industrial solid waste materials and nanomaterials in sustainable concrete production.

FOCUS

- Effects on mechanical properties
- Durability performance
- Environmental impact
- Microstructural characteristics

**Databases:** Google Scholar and related scientific databases.
**Keywords:** waste marble powder, waste glass powder, fly ash, silica fume, e-waste, pumice, nano-silica, nano-$CaCO_3$, graphene oxide, carbon nanotubes, carbon nanofibers, nano-$TiO_2$.
**Time Frame:** Studies published in the last 20 years.

**Inclusion Criteria**

- Partial replacement of cement, fine aggregate, coarse aggregate, or use as nano-additives
- Mechanical properties such as compressive strength, tensile strength, flexural strength
- Durability parameters such as water absorption, permeability, sulfate resistance, chloride resistance, shrinkage, and ASR resistance
- Microstructural and thermal performance where available

SCREENING PROCESS

Title → Abstract → Full-text assessment based on inclusion criteria.

WASTE MATERIALS

- Marble powder
- Glass powder
- Fly ash
- Silica fume
- E-waste
- Pumice
- Coal ash
- Foundry sand

NANOMATERIALS

- Nano-silica
- Nano-$CaCO_3$
- Graphene oxide (GO)
- Reduced graphene oxide (rGO)
- Carbon nanotubes (CNTs)
- Carbon nanofibers (CNFs)
- Nano-$TiO_2$
- Nano-MgO

Studies were grouped into two broad categories to enable structured comparison of their performance in concrete applications.

**Figure 1: Methodological frame work**

The literature search was carried out using Google Scholar and related scientific databases, with keywords such as industrial waste materials, nano materials, waste marble powder, waste glass powder, fly ash, silica fume, e-waste, pumice, nano-silica, nano-CaCO3, graphene oxide, carbon nanotubes, carbon nano fibers, and nano-TiO2. Studies published over the last 20 years were considered to ensure that the review captured both foundational and recent developments in green concrete research. After screening, the selected studies were grouped into two broad categories: waste materials and nano materials. Waste materials included marble powder, glass powder, fly ash, silica fume, e-waste, pumice, coal ash, and foundry sand, while nano materials included nano-silica, nano-CaCO3, graphene oxide, reduced graphene oxide, carbon nanotubes, carbon nano fibers, nano-TiO2, and nano-MgO.

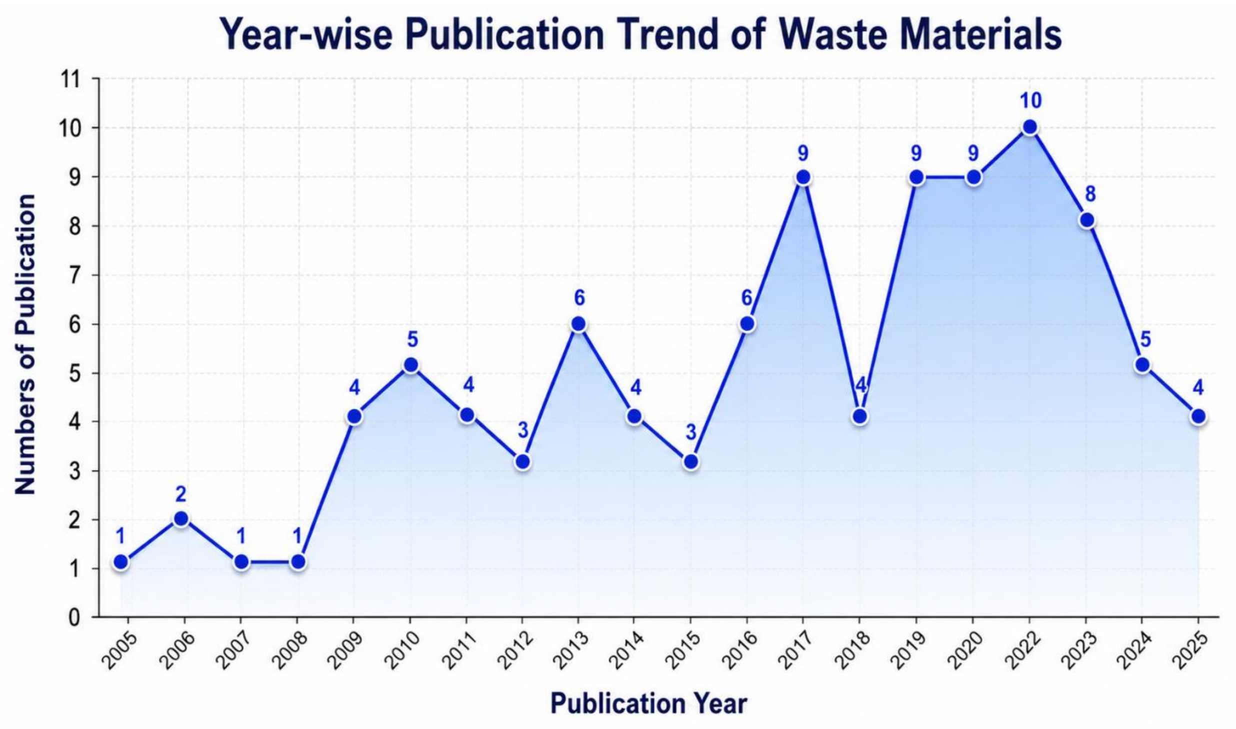


Figure 2: Year-wise publication trend of waste materials

The figure 2 illustrates the year-wise publication trend of waste material research in sustainable concrete from 2005 to 2025. In the initial years (2005–2008), the number of publications was relatively low, ranging from 1 to 2 publications per year, indicating the early stage of research on waste materials in concrete applications. From 2009 onwards, research activity gradually increased, with noticeable growth between 2010 and 2017, reflecting growing awareness of sustainable construction practices and waste utilization. A significant rise in publications was observed after 2016, with the number of studies reaching 9 publications in 2017 and again in 2019–2020. The highest publication output occurred in 2022 with 10 publications, demonstrating peak global interest in incorporating waste materials such as marble powder, fly ash, silica fume, glass powder, coal ash, e-waste, pumice, and foundry sand into concrete production. Although the number of publications slightly declined after 2022, research activity remained relatively high through 2025, indicating the continued importance of waste-based sustainable concrete technologies. Overall, the graph highlights the increasing research focus on reducing environmental pollution, minimizing landfill disposal, and lowering cement consumption through the utilization of industrial and agricultural waste materials in concrete.

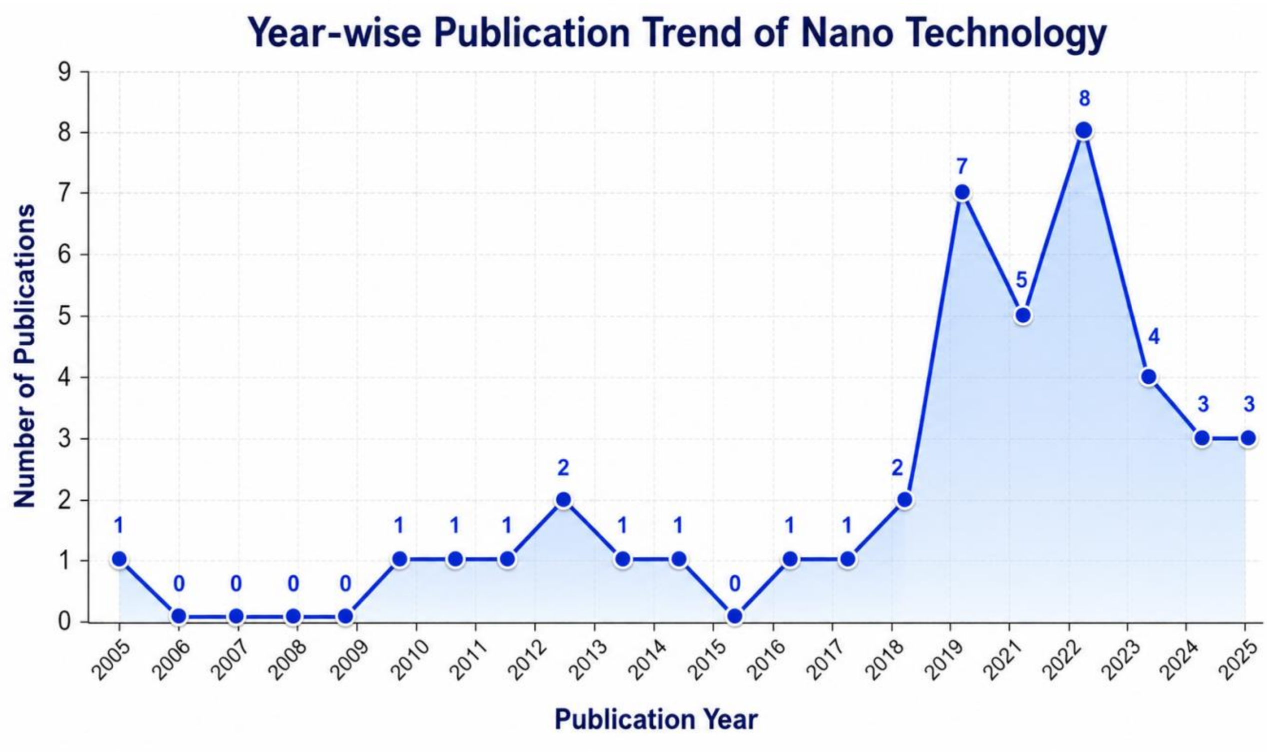
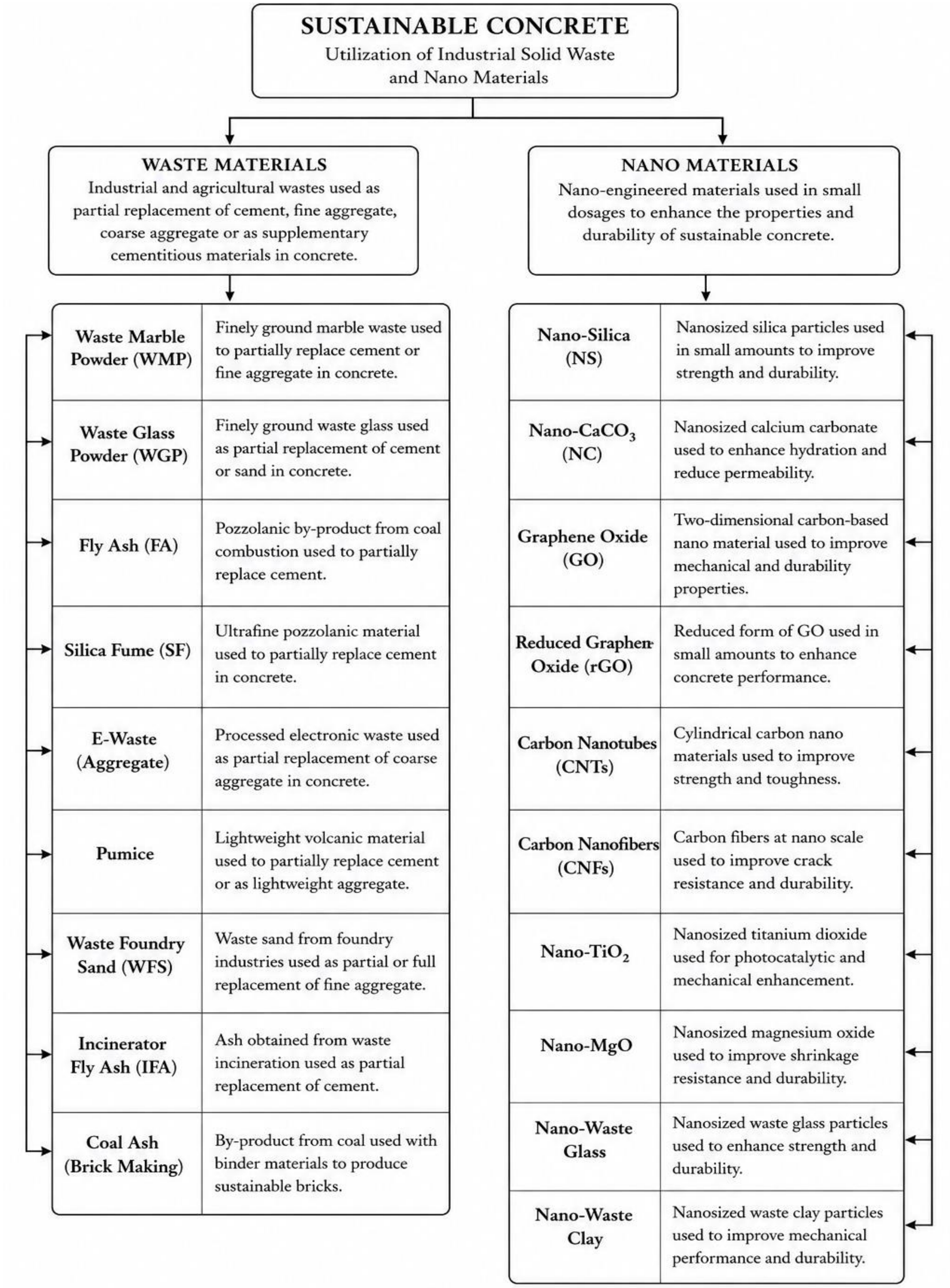


**Figure 3: Year-wise publication trend of nano materials**

The figure 3 illustrates the year-wise publication trend of nanotechnology research in sustainable concrete from 2005 to 2025. During the early years (2005–2018), the number of publications remained relatively low and inconsistent, generally ranging from 0 to 2 publications per year, indicating that nanotechnology applications in concrete were still at an emerging stage. However, a significant rise in research activity began after 2018, with publications increasing sharply from 2 in 2018 to 7 in 2019. Although a slight fluctuation occurred in 2021, the highest number of publications was recorded in 2022 with 8 publications, demonstrating peak research interest in nanotechnology-based sustainable concrete. After 2022, the number of publications gradually declined but remained comparatively high between 2023 and 2025, indicating continued global interest in nano-engineered concrete materials. Overall, the graph highlights the rapidly growing importance of nanotechnology, including nano-silica, graphene oxide, carbon nanotubes, carbon nanofibers, and nano-metal oxides, in improving the mechanical, durability, and sustainability performance of concrete for advanced construction application. The flow chart in figure 4 explain the material and its significance



**SUSTAINABLE CONCRETE**
Utilization of Industrial Solid Waste and Nano Materials

**WASTE MATERIALS**
Industrial and agricultural wastes used as partial replacement of cement, fine aggregate, coarse aggregate or as supplementary cementitious materials in concrete.

| | |
|---|---|
| Waste Marble Powder (WMP) | Finely ground marble waste used to partially replace cement or fine aggregate in concrete. |
| Waste Glass Powder (WGP) | Finely ground waste glass used as partial replacement of cement or sand in concrete. |
| Fly Ash (FA) | Pozzolanic by-product from coal combustion used to partially replace cement. |
| Silica Fume (SF) | Ultrafine pozzolanic material used to partially replace cement in concrete. |
| E-Waste (Aggregate) | Processed electronic waste used as partial replacement of coarse aggregate in concrete. |
| Pumice | Lightweight volcanic material used to partially replace cement or as lightweight aggregate. |
| Waste Foundry Sand (WFS) | Waste sand from foundry industries used as partial or full replacement of fine aggregate. |
| Incinerator Fly Ash (IFA) | Ash obtained from waste incineration used as partial replacement of cement. |
| Coal Ash (Brick Making) | By-product from coal used with binder materials to produce sustainable bricks. |

**NANO MATERIALS**
Nano-engineered materials used in small dosages to enhance the properties and durability of sustainable concrete.

| | |
|---|---|
| Nano-Silica (NS) | Nanosized silica particles used in small amounts to improve strength and durability. |
| Nano-$CaCO_3$ (NC) | Nanosized calcium carbonate used to enhance hydration and reduce permeability. |
| Graphene Oxide (GO) | Two-dimensional carbon-based nano material used to improve mechanical and durability properties. |
| Reduced Graphene Oxide (rGO) | Reduced form of GO used in small amounts to enhance concrete performance. |
| Carbon Nanotubes (CNTs) | Cylindrical carbon nano materials used to improve strength and toughness. |
| Carbon Nanofibers (CNFs) | Carbon fibers at nano scale used to improve crack resistance and durability. |
| Nano-$TiO_2$ | Nanosized titanium dioxide used for photocatalytic and mechanical enhancement. |
| Nano-MgO | Nanosized magnesium oxide used to improve shrinkage resistance and durability. |
| Nano-Waste Glass | Nanosized waste glass particles used to enhance strength and durability. |
| Nano-Waste Clay | Nanosized waste clay particles used to improve mechanical performance and durability. |

Figure 4: Flow chart of waste materials

### Sustainable /green concrete

### Waste marble powder

According to Kishan et al. [1], replacing fine aggregates with up to 50% WMP increased compressive strength; however, greater percentages resulted in decreases. Similarly, Tayeh [2], Rai et al. [5], Tewodros Getachew et al. [15], Ofuyatan et al. [13], and Sonu Pal et al. [8] found that substituting powdered wastes, such as marble powder, for cement at levels of 10–30% led to a decrease in workability and a decrease in compressive strength. These results are in line with those of Abdul Ghani et al. [12], who discovered that mechanical qualities improved up to a specific percentage of WMP inclusion, with 40% sand replacement yielding the best compressive strength.

Studies show that when WMP content increases, workability trends consistently decline. According to Tayeh [2,11], Abdul Ghani et al. [12], and Sahil Patial and Sharma [10], higher WMP levels result in lower slump values and poorer workability, frequently because of increased surface area and water consumption. Despite this disadvantage, WMP has been shown to improve durability in a number of experiments. For instance, WMP can effectively reduce the alkali-silica reaction (ASR), enhancing long-term durability, according to Kishan et al. [1], while Abdul Ghani et al. [12] found that water permeability dropped as WMP content increased. Furthermore, Belouadah et al. [9] discovered that adding WMP decreased shrinkage, outperforming glass powder in this regard.

According to the literature, the ideal replacement amounts typically fall between 5–15% cement substitution and 25–40% fine aggregate substitution. Improvements in flexural, tensile, and compressive strengths are regularly noted at these levels [1, 8, 12, 13, 14, 15]. Both mechanical qualities and workability tend to decline beyond these limits.

All things considered, the reviewed research highlight the two advantages of WMP in concrete. By lowering waste disposal and preserving natural sand and cement resources, it improves specific mechanical and durability qualities within the ideal replacement range and supports sustainable building [1, 9, 12].

The incorporation of waste marble powder (WMP) into concrete has been extensively explored to enhance mechanical properties and reduce environmental impacts associated with marble waste disposal. Several researchers have reported that the partial replacement of cement or fine aggregates with WMP leads to improvements in strength characteristics up to an optimum level, after which strength tends to decline.

### Waste Glass Powder

Concrete reached its maximum strength at 10% glass powder replacement, with strength declining at greater levels, according to Negim et al. [16], Singh and Jain [17], Tamanna and Tuladhar [18] and Sharma and Sangamnerkar [21] It's interesting to note that workability improved with more glass powder, but this highlighted the necessity of longer curing times and more evenly distributed particles for effective results at greater dosages.

Glass powder (ground <600 µm) increased strength most dramatically at 20% cement replacement, according to Rehman et al. [19], who attributed the improvement to pozzolanic processes and the creation of more C-S-H gel. In a similar vein, Gautam et al. [22] found that concrete with 20% cement replacement retained high strength without adverse consequences, while glass powder finer than 100 µm showed pozzolanic activity. While highlighting the affordability of WGP, Rohitha and Yeswanth [27] discovered that the compressive and flexural strengths of concrete with 20% glass powder supplementation were comparable to control concrete. Waste glass added up to 20% to rubberized concrete systems improved durability characteristics such water absorption, shrinkage resistance, and acid resistance while also increasing compressive and tensile strength by 24% and 30%, respectively [42].

The role of particle fineness has been emphasized by multiple researchers. Rehman et al. [19] demonstrated that glass powder below 600 µm enhanced pozzolanic activity. Toro et al. [20], however, found that substituting cement with glass powder (d50 = 16 µm) increased air content and reduced density, though consistency remained within fluid concrete limits. This highlights the dual effect of fine glass particles—while improving strength through pozzolanic activity, they may adversely affect fresh properties such as density and air content,while Gautam et al. [22] confirmed similar benefits for particles below 100 µm.

Glass powder integration has similarly important durability consequences. According to Rehman et al. [19], early alkali consumption of glass particles improved long-term durability by reducing the expansion of the alkali-silica reaction (ASR). Ibrahim [26] also showed that replacing fine aggregate with waste glass up to 40% maintained compressive and tensile strengths, while 15% replacement resulted in a 25% increase in compressive strength and a 37% increase in tensile strength, along with reduced density and improved workability. Spiesz et al. [24] similarly investigated concretes with treated and untreated waste glass, reporting adequate mechanical performance along with enhanced durability, translucency, and air-purifying capacity due to the photocatalytic activity of $TiO_2$.

Several publications emphasize the benefits of WGP from an environmental and sustainability standpoint [25]. Glass powder makes concrete more economical and ecologically friendly by lowering unit weight, porosity, and water absorption, as demonstrated by Shubham et al. [23]. Its potential for structural applications while supporting environmentally and socially conscious building was highlighted by Batham [28]. Additionally, waste glass was positioned among other industrial by-products by Nilesh et al. [29], indicating its potential as a partial substitute in cementitious systems.

Overall, research demonstrates that when used in appropriate quantities, waste glass powder can improve the mechanical and durability performance of concrete. Maximum compressive strength is frequently reached at 10% cement replacement [16, 18, 21], and compressive, tensile, and flexural characteristics greatly improve with 20% replacement (cement or sand) [17, 19, 22, 27, 42]. Reductions in strength, density, or workability are commonly observed at greater substitution levels [16, 20]. WGP is still a viable additive for the construction of sustainable concrete, nonetheless.

Waste glass powder (WGP) has been widely investigated as a supplementary cementitious material and fine aggregate replacement in concrete, owing to its pozzolanic activity, availability, and potential for reducing environmental impacts. Several studies indicate that the performance of concrete incorporating WGP depends largely on replacement levels, particle fineness, and curing duration.

### Silica Fume and Fly Ash

The deterioration-resistant coefficient of compressive strength, relative dynamic elastic modulus (RDEM), and microstructural evaluation were used to monitor the performance of concretes with w/b ratios of 0.38 and 0.33 that contained fly ash (FA: 10–25% by mass) and silica fume (SF: 5–11%) exposed to freezing–thawing in 5% and 10% $Na_2SO_4$. Under 5% $Na_2SO_4$, both SF and FA increased resistance to sulfate assault, with SF outperforming FA. The synergistic harm of coupled sulfate and freeze-thaw was highlighted by the notable rise in resistance of plain OPC concrete up to about 125 freeze-thaw cycles, followed by deterioration. Optima were grouped around 5–8% SF and 25% FA [30].

Nanoscale hybridization provides significant synergistic benefits beyond binary SCM systems. Tavakoli and Heidari [31] substituted 5–10% SF and 0.5–1% nano-$SiO_2$ for cement, indicating a 42.2% increase in compressive strength at 10% SF + 1% nano-$SiO_2$ compared to control, along with decreased water absorption. These findings corroborate the complimentary functions of SF's microfiller action and ultra-fine, highly reactive silica (filling and pozzolanic effects, nucleation sites), which together refine pore structure and speed up C-S-H formation. In general, the literature supports blended designs by identifying residual products like SF and FA as suitable candidates for cementitious systems [34].

Nguyen and Huynh [37] investigated using incinerator fly ash (IFA) in interlocking concrete bricks (0–60% cement replacement) using a densified mixture design algorithm (DMDA) framework, broadening the waste spectrum. While increasing water absorption and voids, increasing IFA content decreased compressive strength, abrasion resistance, bending strength, and bulk density; SEM showed increasingly less-homogeneous microstructures at higher IFA levels. Despite these drawbacks, DMDA-optimized mixtures satisfied Vietnamese standards, showing that strict particle-packing and proportioning techniques can somewhat mitigate the negative effects of difficult waste streams and provide standard-compliant, sustainability-focused goods [37].

Differential scanning calorimetry showed that blending with Class C FA (10–30%) in sulfate-resisting Portland cement (SRPC) systems accelerated hydration up to four weeks. The presence of calcium sulphoaluminate (CSA) in FA and increased C-S-H from pozzolanic reactions improved early strength and setting [46]. This demonstrates the context-dependent nature of FA's benefits: when combined with a sulfate-resistant clinker and assessed at early ages, FA can function as a chemical and microstructural modifier, enhancing early kinetics in addition to longer-term durability characteristics seen elsewhere [30].Sustainable self-compacting concrete (SCC) systems that use recycled coarse aggregates (RCA: 50–100%) and high SCM contents (50–75% in binary/ternary/quaternary blends) at the structural-mixture scale show that combining FA, slag, and SF can improve fresh properties (filling ability, passing ability, viscosity, segregation resistance) while compensating for strength penalties caused by RCA. Judicious SCM synergy restores or surpasses compressive strength in comparison to traditional SCC and maximizes sustainability by lowering the demand for cement and virgin aggregate, according to a research of 23 mixes at w/b of 0.35–0.45 [47]. These results connect mixture-scale performance in highly workable concretes with material-scale reactivity (as in [30], [31], [46]).

In parallel, energy-intensive fired clay units are replaced by unburnt CA bricks, which offer a binder-rich route. Bricks were made with different amounts of cement, 60% coal ash, and 10% lime (by weight).In addition to achieving 19 MPa compressive and 2.1 MPa flexural strength, the ideal formulation—10% cement, 10% sand, and 10% quarry dust with 3 s forming—also minimized water absorption and efflorescence and had a lower unit weight than traditional clay bricks. According to a cost comparison, the CA bricks are economical because they save energy during fire and make good use of ash fines [38].

Supplementary cementitious materials (SCMs) have been shown to improve sustainability and durability, especially under linked degradation mechanisms, according to research.

### E- Waste

Particle-size bands <10 mm, 10–15 mm, and up to 20 mm were investigated for the partial replacement of natural coarse aggregate with e-waste at a rate of 5–30%. Regardless of particle size, strength gains reverted after 15% and were considered unfeasible for building. In order to produce performance-competitive mixes and divert challenging-to-dispose electronic trash from landfills, the typical stiffness and interfacial transition zone issues associated with polymer-rich e-waste aggregates can be mitigated through controlled gradation and moderation of replacement level.

### Pumic

Volcanic pumice is a high-porosity, lightweight aggregate. When volcanic pumice is substituted for aggregate in porous concrete, its inherent vesicular structure increases total porosity and decreases elastic modulus, with only a little decrease in strength when compared to porous mixes using conventional aggregate. Pumice mixes demonstrated potential as impact-energy-absorbing concrete in addition to hydraulic performance, suggesting a market where controlled compliance is beneficial [40].

Although 10–25% pumice enhanced 90-day mechanicals, pumice often decreased early-age strength, validating later-age pozzolanic benefits.

In line with pore refinement, NC (1-3%) significantly increased strength with relatively slight permeability disadvantages. Flexure was significantly enhanced by fibers [41].

Waste foundry sand as a fine aggregate rich in silica. WFS is a reliable partial or complete replacement for fine aggregate in concretes, bricks/blocks, and pavers due to its high $SiO_2$ concentration and uniform granular gradations from ferrous/non-ferrous casting. Although reported systems exhibit physical, mechanical, microstructural, and durability variations that rely on replacement amount and mixture design, there is a wide range of potential applications, providing a way to reduce the extraction of river sand while increasing the value of a plentiful industrial by-product [50].

**Nano technology in Supplementary Cementitious Material:**

Nanotechnology has emerged as a transformative field in concrete technology due to its ability to significantly enhance the microstructural, mechanical, and durability properties of cementitious materials. The incorporation of nanomaterials such as nano-silica, nano-alumina, carbon nanotubes (CNTs), and other nanostructured admixtures has shown promising results in improving concrete performance.

Alkali-activated binary concrete (AABC) using natural pozzolan and granulated blast furnace slag demonstrated compressive strengths of up to 43.4 MPa at 360 days, proving that nanoparticle-modified binders can serve as viable alternatives to ordinary Portland cement (OPC) in terms of long-term strength and durability [33]. More broadly, nanotechnology contributes to concrete by improving mechanical properties, thermal stability, corrosion resistance, and even enabling self-healing capabilities, thus extending service life and reducing lifecycle costs [48].

Among various nanomaterials, nano-silica has been the most widely studied due to its ability to refine pore structure and accelerate pozzolanic reactions. Experimental studies confirm that nano-silica, particularly when combined with silica fume and steel fibers, enhances compressive, flexural, and tensile strengths at both early and later ages. For instance, compressive strength improvements of 40–41% and flexural strength gains of 23–42% were reported across 3–28 days, with SEM micrographs showing denser, more homogeneous microstructures compared to mixes without nano-silica [32]. Similarly, a 10% replacement of cement with nano-silica not only raised compressive strength to 129.48 MPa at 28 days but also improved resistance to sulfate attack, highlighting its role in both strength and durability enhancement [36].

Recent reviews emphasize that nanotechnology can impart multifunctional properties to concrete, such as self-cleaning, self-sensing, and self-compacting behaviors, while also promoting environmental benefits through waste reduction and improved efficiency. However, concerns remain regarding the environmental impacts of large-scale nanoparticle production and the need for safe handling protocols [39].

Nanotechnology applications are not limited to silica-based additives. The use of nanostructured mineral admixtures prepared through high-energy ball milling of industrial byproducts such as spent catalysts, copper slag, and cement kiln dust has also been explored. These materials, when used as partial cement replacements, yielded compressive strength improvements of up to 33% and reduced water absorption by 44%, owing to a denser interfacial transition zone (ITZ) [44][45].

Moreover, nano-modified concretes show potential in geopolymer systems. The addition of nanoparticles contributes to the formation of additional C–S–H, N–A–S–H, and C–A–S–H gels while refining the pore structure, thereby improving the strength and durability of geopolymer composites [43]. Advances in cleaner technologies also point toward integrating CNTs and self-sensing CNT composites into concrete to further improve stiffness, strength, and multifunctionality [35].

Collectively, these studies demonstrate that nanotechnology plays a pivotal role in advancing high-performance and sustainable concretes. While nano-silica remains the most effective and widely used additive, emerging nanomaterials such as alumina nanoparticles, CNTs, and nanostructured industrial byproducts show great promise. Future work should focus not only on optimizing dosage and dispersion techniques but also on addressing environmental and economic aspects for large-scale applications.

### Nano-silica (NS)

Recent advancements in concrete technology highlight nano-silica (NS) as a promising additive for enhancing mechanical performance, durability, and sustainability. Multiple studies have examined NS's effects on concrete properties across varying dosages, binder compositions, and functionalizations, providing a comprehensive understanding of its potential [51–55].

NS improves early-age strength and accelerates hydration due to its high pozzolanic activity and nano-filler effect. For example, incorporating 1% NS into concrete with 30% ground granulated blast-furnace slag (GGBS) increased compressive strength significantly within the first week, while higher dosages (2%) yielded reduced benefits due to agglomeration and limited calcium hydroxide availability. Flexural performance mirrored compressive strength trends, with SEM and RCPT analyses confirming microstructural densification [51]. Hydrophobic NS further enhanced strength but showed mixed results in corrosion resistance due to potential ionic ingress despite improved compactness [52].

NS refines concrete microstructure, reducing porosity and chloride permeability, and improving bond strength at the paste-aggregate interface. Studies using SEM, EDS, and XRD confirm that NS consumes calcium hydroxide and forms additional C-S-H gel, reducing the Ca/Si ratio and creating a denser matrix [54]. Enhanced acid and carbonation resistance has been observed, with NS-modified concretes showing exceptional durability under sulfuric acid exposure. However, NS increases water demand and reduces workability, requiring admixtures to maintain flowability [51, 52].

Literature reviews emphasize that NS performance depends on dosage (commonly 2–3% by cement weight), particle size, purity, and dispersion. Excessive NS can cause agglomeration and reduced workability, while appropriate dispersion methods, surfactants, and morphological control improve effectiveness. Combining NS with supplementary cementitious materials or fibers can enhance the properties of recycled aggregate concretes and multi-component mixes [53]. Research gaps include the long-term behavior of NS concretes in aggressive environments and at structural scales.

An emerging area is the synthesis of NS from agricultural waste (e.g., rice husk, sugarcane bagasse ash) as an eco-friendly alternative to traditional methods. These approaches reduce environmental impact and support circular economy practices. Techniques such as sol-gel, precipitation, and hydrothermal treatments have produced high-purity NS suitable for construction applications, though process optimization and scale-up remain priorities [55].

Key needs include improving NS dispersion to avoid agglomeration, evaluating rheological behavior, studying fiber-matrix interactions, and assessing NS under thermal, marine, and fire conditions. Integrating NS with other nanomaterials and admixtures may balance workability and strength. Modeling and life-cycle assessments will be critical for mainstream adoption .

### Nano-$CaCO_3$

Research on nano-calcium carbonate (Nano-$CaCO_3$) in concrete and related composites has grown rapidly, focusing on improving mechanical properties, durability, and sustainability. Studies have evaluated its role as a cementitious additive or partial replacement, often in synergy with waste materials, recycled aggregates, or supplementary cementitious components [56–60].

Nano-$CaCO_3$ accelerates hydration by providing nucleation sites, forming additional C-S-H gel and carbo-aluminates. It refines pore structures, reduces sorptivity, chloride ingress, and corrosion risk. Dosages of 1–2% typically enhance early-age strength and microstructural density, but higher contents reduce workability and may lower strength due to agglomeration. Setting times decrease with increasing Nano-$CaCO_3$, requiring water-reducing admixtures to maintain flowability [57].

When combined with recycled coarse aggregates, Nano-$CaCO_3$ can partially offset strength losses from aggregate replacement. However, performance depends on dosage and water-to-cement ratio[58].

In ultra-high-performance concretes (UHPC) containing high ceramic tile waste, Nano-$CaCO_3$ improved workability, shortened setting times, and increased compressive and flexural strengths by up to 38%. It enhanced hydration kinetics, refined ITZ microstructure, and reduced porosity. Sustainability gains included >20% reductions in energy intensity, cost, and $CO_2$ emissions [59].

Fly Ash and Hybrid Mixes: Nano-$CaCO_3$ synergizes with fly ash by enhancing early-age hydration and mitigating fly ash's slow strength gain. SEM analyses confirmed filler and seeding effects as key mechanisms [60].

Further exploration of green synthesis and dispersion technologies could broaden Nano-$CaCO_3$'s use in low-carbon construction.

### Carbon-based nano materials

### Graphene oxide

Graphene oxide (GO) enhances concrete durability by providing nucleation sites, promoting hydration, and reducing porosity. Studies reported 0.03–0.05% GO as an optimal dosage, achieving refined microstructures resistant to chloride and sulfate ingress. Improvements include up to 50% reduction in chloride permeability. However, dispersion and stability in alkaline environments remain challenges, requiring further investigation and field-scale trials for commercialization [61].

Incorporating rGO into waste-based concrete with high levels of GGBS, fly ash, lead smelter slag, and recycled aggregates mitigates strength losses common in such mixes. At 0.1% rGO, compressive, tensile, and flexural strengths improved by 42–47%, while water absorption and shrinkage decreased by 35–45%. Microstructural analysis confirmed reduced porosity and enhanced hydration products. However, workability decreased due to rGO's high surface area, and agglomeration at higher dosages (0.3%) limited benefits. Dispersion and cost remain barriers to large-scale adoption [62].

Environmental analysis revealed reduced embodied $CO_2$ (EI = 5.37 $kgCO_2/MPa$ vs. 6.62 for control). Field validation and cradle-to-grave assessments are needed to confirm long-term environmental gains [63]. Thermal conductivity decreased by 33% at higher GO levels, suggesting thermal insulation benefits. XRD confirmed GO's compatibility with geopolymeric matrices, supporting its potential for sustainable infrastructure using industrial by-products [64].

Performance strongly depends on GO properties, superplasticizer type, and dispersion methods. GO-B (smaller particle size, higher functional groups) outperformed GO-A. Ultrasonic mixing combined with polycarboxylate-based superplasticizers yielded the best results, achieving up to 33% improvement in compressive strength and 24–30% increases in tensile, flexural, and modulus values [65].

Future studies should target scalable dispersion technologies, cost-effective synthesis, field trials under harsh conditions, and integration with sustainable binders and aggregates. Broader life-cycle and durability studies are critical to realizing GO's potential in sustainable, high-performance cementitious systems.

### Carbon nano tubes (CNTs)

Recent studies have highlighted the significant potential of carbon nanotube-enhanced green concrete in addressing environmental and performance-related challenges in the construction industry. In particular, the addition of 0.1% CNTs reduced sorptivity by 28.76%, sulphate-induced mass and compressive strength losses by 50.93% and 48.47%, respectively, and acid attack mass loss by 35.97%, confirming the synergistic effect of CNT filling, bridging action, and RHA pozzolanic reactions in densifying the concrete microstructure [67]. Complementary studies on carbon nanotube concrete also emphasized that CNTs, including both single-walled and multi-walled variants, significantly improve compressive, tensile, and flexural strength, fracture toughness, abrasion resistance, permeability resistance, and self-sensing capabilities even at very low dosages. Owing to their exceptional tensile strength, corrosion resistance, thermal stability, and crack-bridging ability, CNTs are increasingly recognized as promising nano materials for producing high-strength, durable, and sustainable concrete for future construction applications [68].

### Carbon nano fibers (CNFs)

Carbon nanofibers (CNFs) have demonstrated significant improvements in the mechanical performance and durability of concrete due to their nano-scale crack-bridging and pore-filling abilities. Studies reported that the incorporation of CNFs enhanced compressive strength, flexural strength, fracture toughness, chloride penetration resistance, and freeze–thaw durability. An optimal CNF dosage of approximately 0.1–0.5% was found to effectively reduce porosity and permeability while densifying the calcium silicate hydrate (C-S-H) matrix. For example, CNFs reduced concrete porosity by 9.0 wt.% and water permeability by 39.3%, thereby improving resistance to environmental deterioration [69,71,75]. Hybrid CNF systems combined with polyvinyl alcohol fibers further enhanced chloride ion resistance and mechanical behavior through synergistic reinforcement mechanisms [71]. Moreover, CNFs improved fire endurance and crack resistance in high-strength concrete exposed to elevated temperatures up to 800 °C by effectively bridging microcracks and limiting structural degradation [69]. Microstructural investigations using SEM, MIP, and EDS confirmed that CNFs refine pore structure, reduce microcracking, and strengthen the interfacial transition zone within cementitious composites [73,75].

### Nano-titanium dioxide (Nano-$TiO_2$)

Nano-titanium dioxide (Nano-$TiO_2$) has been widely investigated for its photocatalytic, self-cleaning, and mechanical enhancement properties in concrete. Research indicates that Nano-$TiO_2$ improves hydration reactions, refines pore structure, and increases compressive and flexural strengths while simultaneously imparting self-cleaning and air-purifying capabilities. The photocatalytic activity of Nano-$TiO_2$ enables degradation of pollutants such as NOx and organic contaminants when exposed to sunlight, making it suitable for sustainable urban infrastructure [70,72]. Studies showed that appropriate Nano-$TiO_2$ particle size and dosage significantly improved hardened concrete properties, reduced permeability, and enhanced durability while maintaining acceptable workability [72,74]. Additionally, Nano-$TiO_2$ contributes to denser microstructures by accelerating cement hydration and promoting the formation of additional C-S-H gel, which improves resistance against chloride penetration, carbonation, and surface contamination [73,74]. These characteristics make Nano-$TiO_2$ concrete highly suitable for environmentally friendly and low-maintenance construction applications [70,74].

### Nano-magnesium oxide (Nano-MgO)

Nano-magnesium oxide (Nano-MgO) has emerged as an effective nano-additive for improving shrinkage resistance, durability, and mechanical performance in cement-based materials. Research has shown that Nano-MgO contributes to expansive hydration products, which compensate for shrinkage and reduce crack formation in concrete. The addition of Nano-MgO enhances compressive strength, refines pore structure, and improves resistance to sulphate attack, chloride ingress, and carbonation by densifying the cement matrix [73,76]. Nano-MgO particles also accelerate cement hydration and promote the formation of magnesium silicate hydrate (M-S-H) gel, which contributes to improved long-term durability and dimensional stability [74]. Furthermore, studies have highlighted the effectiveness of Nano-MgO in mitigating autogenous and drying shrinkage, especially in high-performance and self-compacting concretes, thereby enhancing structural longevity and sustainability in aggressive environmental conditions [76, 77].

## Conclusion

The concrete structures prepared from the waste materials have lower environmental impact through reduced $CO_2$ emission and maintain all the specification of "Green Concrete". The significance of this study is to encourage the usage of solid waste to minimize the disposal cost of waste materials, decrease the environmental risk of pollution and save the landfill space.

Industrial waste material like fly ash, silica fume, waste glass, waste marble powder, e waste and pumic can be added in concrete as cement and sand and aggregate substitution. the optimum dogaes varies however mostly wate material gives results under 30% replacement. Compressive strength , tensile strength, flexural strength increases densifying the microstructure and increasing the resistivity against weather and water. Nano science is the science of studying, controlling, and re-engineering of particles at the atomic and molecular level. The size of the particles is the main reason for using this science as the material's properties are highly altered under a Nano scale. Nanoparticles can be in the form of a powder, fibre, crystal, or pipe. It can be used as it is or can be deployed to reach the desired characteristics. Nano materials like nano silica, carbon nano tubes, graphene oxide, nano fibers, nano titanium oxide, nano magnesium oxide demonstrated significant improvements in the mechanical performance and durability of concrete due to their nano-scale crack-bridging and pore-filling abilities. Studies reported that the incorporation of nano materials enhanced compressive strength, flexural strength, fracture toughness, chloride penetration resistance, and freeze–thaw durability. Self-compacting concrete flow ability, passing ability, and viscosity declined as the NS, NWG, and NWC increased optimum dosage of nano materials is .1%.Waste-milled nano materials are comparable to nano-silica, which is chemically prepared to improve SCC mechanical properties and purify the microstructure. However the dispersion method becomes critical and necessity of adding super plasticizers or water reducers is ensured as the finer particles agglomerates in concrete making weak zones. So further studies should be done on dispersion methods, aggressive environment exposure, long term durability of these waste materials

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## Conflict of interest

Author has no conflict of interest.

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