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GRAPHENE: 3D PRINTING FOR NEXT-GENERATION SUSTAINABLE AND SMART BUILDINGS

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Abstract. Graphene 3D printing is an encouraging technology for sustainable and smart building construction. Graphene and its derivatives increase the thermal, mechanical, electrical, and rheological properties of printed cementitious and geopolymer materials. They increase interlayer bonding, printability, durability, crack resistance, and thermal performance while permitting the self-sensing competencies. This review describes important 3D printing methods, constructional applications, existing developments, and challenges, comprising rheological optimization, graphene dispersion, and standardization. Briefly, the graphene-based 3D printing delivers a strong prospect for durable, lightweight, energy-effective, and low-carbon future building construction.
Keywords: Graphene 3D printing, Nanomaterials, Sustainable construction, Smart buildings, Challenges anf future perspectives

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1. Introduction. There is a great demand for sustainable, automated, earthquake protective and intelligent building systems globally [1]. The conventional construction methods utilise huge amounts of raw materials and energy. Besides, these methods release green gases and aerosols into the atmosphere. The cement production is only responsible for about 7-8% of global carbon dioxide emissions. Consequently, the increasing urbanization and infrastructure needs require stronger, faster, and more sustainable construction skills. Nowadays, 3D printing (C3DP) is gaining attention in manufacturing many small articles and commodities. Also, research is going on for fabricating buildings layer-by-layer directly by 3D printing. This technology provides many benefits comprising fast construction, no pollution, reduced labour, freedom of design, minimum material waste, and enhanced construction safety.

Of course, cementitious materials exhibit numerous qualities, but they cannot be used in 3D printing. For 3D printing, the material should be in liquid or paste form at the working temperature of the 3D printing machine. Therefore, the scientists and engineers are exploring suitable materials for this purpose. Nowadays, this is the era of nanotechnology and hence, nanomaterials have been explored for 3D printing purposes to construct buildings; to improve the performance of printable construction materials. Among many nanomaterials, graphene has been recognised as the best material for 3D printing to construct buildings; of course, in the initial stage at this time. Graphene has emerged as one of the most capable nanomaterials for building construction due to its unique features.

The use of graphene in 3D printing is gaining importance as an encouraging building construction material [2]. The research is going on in this area and no review is available on this topic. Therefore, attempts were made to describe the latest development in 3D printing using graphene for building construction. This review article broadly describes the recent developments in graphene 3D printing in building construction and identifies the future research directions for industrial applications.

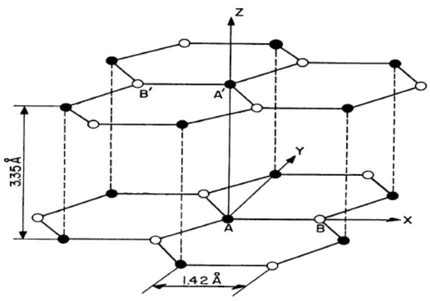
Graphene as a building material. The graphene is considered the material of this century with remarkable properties. The graphene and its derivatives (Figure 1) are used for various applications. The graphene, graphene derivatives, and graphene-based composites are being

considered as the best 3D printing nanomaterial for building construction in the future. This is due to high specific surface area, good tensile strength (~130 GPa), Young's modulus (1.0 TPa), thermal, electrical, rheological, and thermal multifunctional properties (Table 1). Besides, graphene-based materials also increase rheological properties like viscosity, extensibility, and shape retention, which are important for stable 3D printing. Additionally, they enhanced the resistance against water infiltration, chloride attack, and chemical depletion. Furthermore, the graphene composites offer self-sensing ability for crack detection and structural health checking, making them appropriate for future smart and sustainable building materials. This is due to their electrical conductivity and piezoresistive behaviour [3].

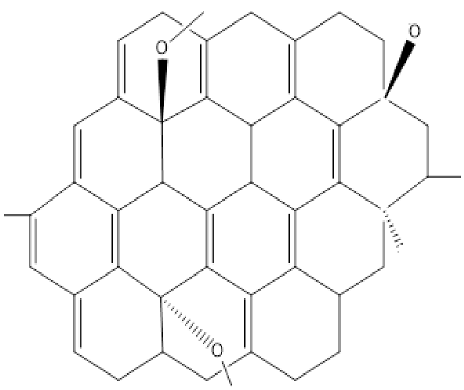
Unlike conventional 3D-printed concrete, graphene did not show brittleness, shrinkage cracking, low tensile strength and weak interlayer bonding. In geopolymer or cementitious systems, graphene acted as a nano-reinforcement material, which increases load transfer, crack bridging, pore refinement, and interfacial bonding, thus refining toughness, durability, compressive strength, and interlayer adhesion. The graphene oxide is useful due to its oxygen having functional groups, which improve the dispersion and interactions with cement hydration products, giving denser microstructures. The graphene-based or mixed materials can considerably increase cement hydration, improve pore structure, decrease crack chances and reinforce the interfacial transition zone in cementitious matrices. Furthermore, the graphene-containing material introduces multifunctional features like self-sensing, thermal control, electromagnetic protection and structural health monitoring.

Several graphene derivatives are being utilized in construction materials. The most important is graphene oxide (GO), which contains oxygen functional groups like epoxy, hydroxyl, and carboxyl groups. These functional groups increase the dispersibility in water systems and expedite the interactions among the cement hydration products. The nest material is reduced graphene oxide (rGO), which possesses partially restored graphitic features and enhanced electrical conductivity compared to GO. The graphene nanoplatelets (GNPs) are multilayer graphene sheets. These have good mechanical reinforcement and lower production prices. The 3D graphene-based foams, aerogels, and sponges are used to provide lightweight porous constructions with improved mechanical stability features.

Graphene crystal



Graphene oxide



Reduced graphene oxide

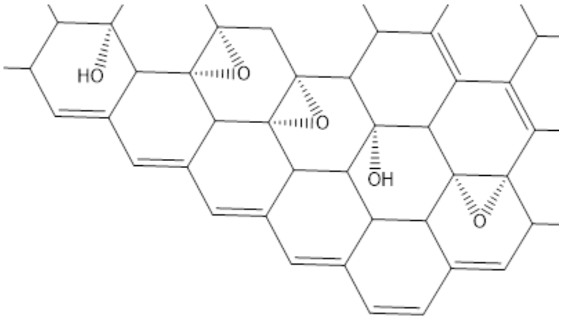


Fig.1. Structure of graphene and its compounds

Table 1. Graphene properties for 3D-printed building construction

Properties	Typical values	3D Printing construction benefits
Specific surface area	~2630 m^2/g	Increases interaction with cement hydration products
Thermal conductivity	3000–5000 W/m.K	Increases thermal management
Electrical conductivity	~10^6 S/m	Enables self-sensing and smart structures
Young's modulus	~1.0 TPa	Improves stiffness of printable composites
Tensile strength	~130 GPa	Progresses crack resistance and structural strength
Density	~2.2 g cm^{-3}	Gives lightweight structures
Impermeability	Nearly impermeable	Increase durability and water resistance
Tensile strength	~130 GPa	Increases crack resistance and structural strength

There are different types of printing techniques for graphene-based construction materials. The extrusion-based printing is the dominant technique for graphene-cement composites due to its scalability and simplicity [6]. The most important advantages are high material efficiency, continuous deposition and large-scale applicability. However, rheology control, nozzle clogging and dispersion stability remained the limitations. The direct ink writing (DIW) is a method of 3D printing. This allowed the precise deposition of graphene with controlled micro-structures. Recently, robotic additive manufacturing has gained attention in 3D printing construction. The robotic systems provided good flexibility for complex architectural designs, geometries and large-scale infrastructure construction. The major advantages of using graphene materials in 3D printing are given in Table 2. The printing, assembly, mechanism and constructed structures are shown in Figure 2.

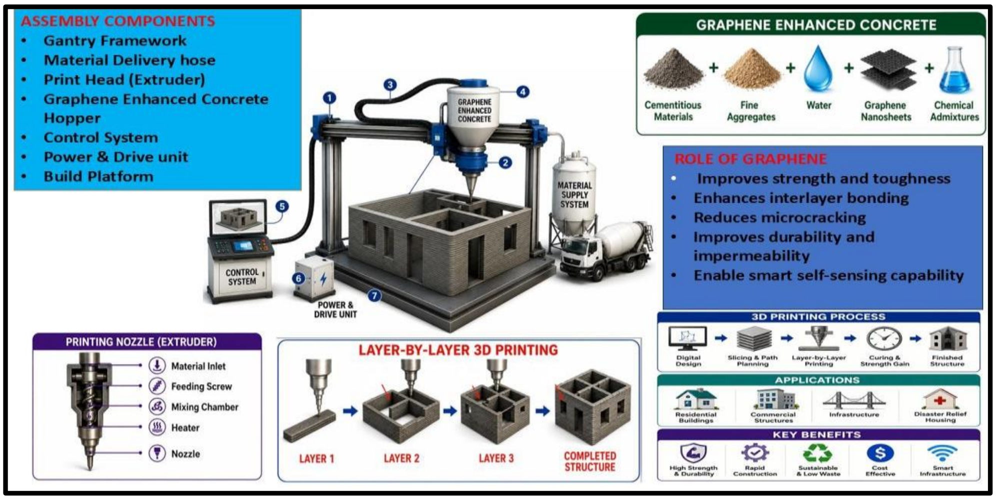


Fig.2. Printing, assembly, mechanism and constructed structures

Table 2. Advantages of using graphene materials in 3D printing

Advantages	Effect on construction materials
Pore alteration	Gives denser microstructure
Crack bridging	Decrease microcrack propagation
Improved interlayer bonding	Increases structural integrity
Better rheology	Increases printability and shape retention
Good thermal conductivity	Increases energy efficacy
Augmented durability	Good resistance against chemical attack
Good electrical conductivity	Permits structural health checking

2. Role of graphene in 3D printed construction materials. The use of graphene in construction materials is very important. The most important is rheological modification. This is due to the fact that the printable materials need optimized rheological properties. The most important properties are buildability, extrudability, pumpability and shape retention. For example, the GO nano-sheets can improve rheology because of their high surface area and interactions with water molecules [7,8]. Besides, GO enhanced the yield stress and viscosity, preserving the printability. The mechanical enhancement is another role of graphene in building materials. The graphene-based materials enhanced the mechanical strength. The several mechanisms involved are the pore refinement, crack bridging, load transfer enhancement, nucleation of hydration products and improved interfacial bonding. The studies have shown that the use has shown considerable increases in tensile, compressive, and flexural strength. The interlayer bonding improvement is an important additive construction. The graphene nano-sheets increase the interfacial cohesion by endorsing the hydration reactions and decreasing the void formation among the deposited layers. The graphene materials also provide good durability to the building. The durability is provided by refining pore structure, reducing permeability, improving freeze-thaw stability, increasing chemical resistance and reducing chloride penetration [9]. These are the features needed for long-term infrastructure applications.

3. Graphene-based materials. Generally, graphene and its compounds are mixed with the cementitious materials. The GO accelerated the cement hydration by performing as nucleation sites for calcium silicate hydrate (C-S-H) formation. The enhanced hydration kinetics resulted in denser micro-structures and greater strength development. The geopolymers are sustainable substitutes for Portland cement and the addition of graphene improved the material features. Most importantly, the geopolymer conductivity, strength, and crack resistance were reduced [10-12]. The graphene-based composites showed piezoresistive behavior, permitting the real-time structural fitness monitoring.

The different of graphene materials are given in Table 3, while Table 4 shows a comparison between conventional and graphene-enhanced printable concrete.

Table 3. Classes of graphene materials

Graphene materials	**Major characteristics**	**Construction applications**
Graphene oxide (GO)	Hydrophilic & oxygen functional groups	Improves dispersion and cement hydration
Reduced graphene oxide (rGO)	High electrical conductivity	Smart sensing infrastructure
Graphene nano-platelets (GNPs)	High mechanical strengthening	Strength enhancement
Graphene aerogels	Porous lightweight constructions	Thermal insulation
Graphene-polymer composites	Elastic and conductive	Smart building components

Table 4. Comparison between conventional and graphene-enhanced printable concrete

Properties	Conventional printable concrete	Graphene-based printable concrete
Crack resistance	Limited	Excellent
Tensile strength	Moderate	High
Interlayer bonding	Weak	Improved
Thermal performance	Moderate	Improved
Electrical conductivity	Low	Excellent
Self-sensing capability	Absent	Present
Durability	Moderate	High

4. Multifunctional applications of graphene in next-generation buildings. The graphene and its compounds are the choice in multifunctional applications to construct next-generation buildings. The smart graphene-based infrastructure provides stress sensing, self-monitoring ability, damage detection and real-time data acquisition. The thermal management is also controlled by the addition. The graphene also controls energy efficiency in buildings, decreasing heating and cooling needs. The electromagnetic interference shielding is another important benefit in new-generation buildings. This is achieved by protecting buildings from electromagnetic radiation and shocks. The light of this material allowed the fabrication of robust portable house systems to avoid any loss in earthquakes. This is the concept of sustainable housing, reducing cement use and carbon emissions. The detailed protocol of 3D printing of graphene and its material in building construction is given in Figure 3.

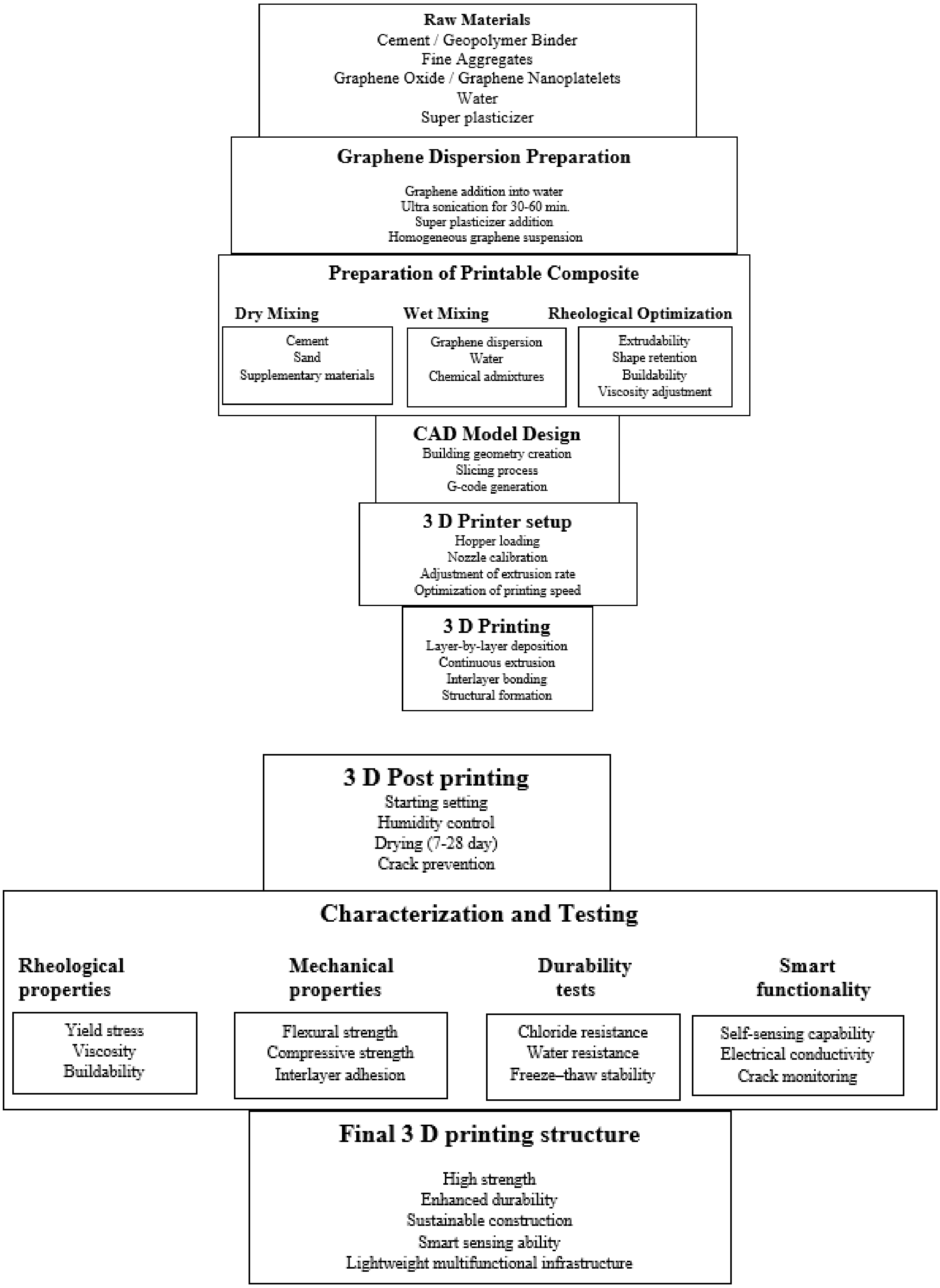


Fig. 3. Schematic illustration of graphene-based three-dimensional (3D) printing and material processing protocols for sustainable building construction

5. Current status of graphene in 3D-printed building construction. The 3D printing of graphene in building construction is in its development stage, as no example is available where graphene has been used as a 3D printing material for large industrial or community buildings.

However, the research is going on in this direction. Some lab batch and pilot-scale projects have shown the probability of graphene 3D printed construction. The Versarien (UK) prepared the “Lunar” pod using graphene-based Cementene™ concrete. The material is considered one of the first graphene 3D printed building structures. In this work, Cementene™ (a graphene cement additive) was used for concrete 3D printing for studios, office pods, leisure spaces and emergency shelters. These items showed good printability, strength, curing behaviour and sustainability. This project was the earliest graphene integration nanotechnology program.

Another program was started at the University of Virginia, Graphene-LC2 3D Printed Concrete. The researchers at the University of Virginia prepared a graphene printable concrete utilising limestone claimed clay cement (LC2). This showed 1% reduction in carbon emissions and about 23% increase in mechanical performance. The researchers at RMIT University also prepared GO-modified concrete for smart buildings. The GO-based material improved printability, electrical conductivity, crack sensing capability and stability of cementitious layers. It was realised that the material was useful for structural health monitoring, smart infrastructure for intelligent buildings and automatic maintenance systems. Some salient features of graphene-based 3D printing are given in Table 5.

Table 5. Key characteristics and performance attributes of graphene-based materials for three-dimensional (3D) printing in construction

Study/Project	Graphene Materials	Printing Method	Applications	Outcome
Versarien Lunar Pod	Graphene-based cement	Extrusion 3D printing	Buildings/pods	Improved strength&sustainability
Univ. Virginia concrete	Graphene with LC2 cement	Concrete extrusion printing	Sustainable buildings	31% low CO_2 emissions
RMIT Concrete	Graphene oxide	Additive concrete printing	Smart infrastructure	Crack sensing ability
Cement-Free Mortar	Graphene admixture	3D mortar printing	Sustainable architecture	Low cement consumption

6. Challenges. In spite of a bright future, there are some challenges to materialize the 3D printing technology for making houses using graphene and its compounds as building materials. The most important challenges are summarised below.

-Proper optimization of rheological properties due to increased viscosity and reduced printability by adding graphene to the materials.

-Nozzle blockage and extrusion instability may happen in 3D printing due to nanoparticle accumulation.

- Need to develop standard formulations, testing methods, and regulations.

-Potential health and environmental concerns associated with nanoparticle exposure.

-Limited knowledge of interlayer bonding mechanisms in graphene 3D printed structures.

A Summary of research gaps in 3D printing of graphene for building construction is given in Table 6.

Table 6. Research gaps, technical challenges, and future research directions in graphene-based three-dimensional (3D) printing for sustainable and smart buildings

Research Area	Current Limitation	Future Need
Dispersion of graphene	Accumulation	Large-scale dispersion methods
Optimization of rheology	Printability strength	AI-assisted formulation
Determination of durability	Limited long-term studies	Field-scale validation
Cost	Costly graphene synthesis	Low-cost production

Despite these challenges, the ongoing research is expected to overcome all these issues and 3D printed graphene buildings will be a reality in the coming years.

7. Future perspectives. The future of 3D printing with graphene materials in building construction is promising as it combines additive manufacturing, nanotechnology and smart infrastructure. This is due to the fact that graphene improves the durability, mechanical strength, thermal stability, and multi-functionality of the materials. The graphene-made composites light in weight, stronger, and more durable while decreasing cement use and environmental pollution. The development of smart self-sensing buildings is the future use of 3D printing with graphene. This will also support low-carbon and sustainable construction. The additive manufacturing decreases the material waste, while the addition will enhance low-carbon binders working and printable geopolymers. The future robotic additive systems will permit fast and automatic construction of houses, shelters, and remote infrastructures. Additionally, graphene-based materials will provide electromagnetic shielding, thermal insulation, and energy management to the buildings.

8. Conclusion. The graphene-based 3D printed building construction looks like a fascinating approach for next-generation sustainable buildings. Certainly, the 3D printing of graphene for buildings will improve the mechanical, electrical, rheological, thermal, and durability of the materials. The addition of graphene into construction material will enable the development of intelligent, energy-efficient, lightweight, and multifunctional building structures. The research in progress in this direction for removing several challenges. The continued interdisciplinary research comprising nanotechnology, civil engineering, robotics, and computational modelling will make the dream of sustainable buildings true soon. Briefly, the future of graphene-based 3D printing in building construction is quite bright. I hope that in some years time we shall see buildings and sky creepers around made of graphene and its materials using 3D printing.

Author Contributions. I.A. (Imran Ali) conceptualized the study, conducted the literature review, developed the manuscript framework, analyzed the current advances in graphene-based 3D printing technologies for sustainable and smart buildings, interpreted the findings, and wrote the original draft of the manuscript. A.A.B. (Al Arsh Basheer) contributed to the literature review, critically reviewed and edited the manuscript, validated the scientific content, improved the presentation of the work, and approved the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of Interest. The authors declare that they have no competing financial or personal interests that could have influenced the work reported in this manuscript.

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Informed Consent. Not applicable.

References

[1]Narayan, J., & Bezborah, K. (2024). Recent advances in the functionalization, substitutional doping and applications of graphene/graphene composite nanomaterials. *RSC Advances*, **14**(19), 13413–13444. https://doi.org/10.1039/D3RA07072G
[2]Uddin, M. N., Bappy, M. A., Rab, M. F., Znidi, F., & Morsy, M. (2024). Recent progress on synthesis of 3D graphene, properties, and emerging applications. In *Chemistry of Graphene—Synthesis, Reactivity, Applications and Toxicities*. https://doi.org/10.5772/intechopen.114168
[3]Salah, H. A., Mutalib, A. A., Kaish, A. B., Syamsir, A., & Algaifi, H. A. (2023). Development of ultra-high-performance silica fume-based mortar incorporating graphene nanoplatelets for 3-dimensional concrete printing application. *Buildings*, **13**(8), 1949. https://doi.org/10.3390/buildings13081949
[4]Dubey, P. K., & Maurya, M. C. (2026). A comprehensive review of 3D printing in construction: Technology, materials, and digital workflow. *Innovative Infrastructure Solutions*, **11**(1), 51. DOI not available.
[5]Sovetova, M., & Calautit, J. K. (2024). Thermal and energy efficiency in 3D-printed buildings: Review of geometric design, materials and printing processes. *Energy and Buildings*, **323**, 114731. DOI not available.
[6]Guo, H., Lv, R., & Bai, S. (2019). Recent advances on 3D printing graphene-based composites. *Nano Materials Science*, **1**(2), 101–115. https://doi.org/10.1016/j.nanoms.2019.02.003
[7]Baytak, T., Gdeh, T., Jiang, Z., Arce, G., Colosi, L. M., & Ozbulut, O. E. (2024). Rheological, mechanical, and environmental performance of printable graphene-enhanced cementitious composites with limestone and calcined clay. *Journal of Building Engineering*, **97**, 110673. https://doi.org/10.1016/j.jobe.2024.110673
[8]Patil, R., & Alimperti, S. (2024). Graphene in 3D bioprinting. *Journal of Functional Biomaterials*, **15**(4), 82. https://doi.org/10.3390/jfb15040082
[9]Asim, N., Badiei, M., Samsudin, N. A., Mohammad, M., Razali, H., Soltani, S., & Amin, N. (2022). Application of graphene-based materials in developing sustainable infrastructure: An overview. *Composites Part B: Engineering*, **245**, 110188. https://doi.org/10.1016/j.compositesb.2022.110188
[10] Chhetri, S., & Kuila, T. (2024). Polymer composites with 3D graphene architectures as high-performance EMI shielding materials: A review. *RSC Applied Polymers*, **2**(4), 507–533. https://doi.org/10.1039/D4LP00028A
[11] Guo, H., Lv, R., & Bai, S. (2019). Recent advances on 3D printing graphene-based composites. *Nano Materials Science*, **1**(2), 101–115. https://doi.org/10.1016/j.nanoms.2019.02.003
[12] Narayan, J., & Bezborah, K. (2024). Recent advances in the functionalization, substitutional doping and applications of graphene/graphene composite nanomaterials. *RSC Advances*, **14**(19), 13413–13444. https://doi.org/10.1039/D3RA07072G