Chapter

Nanoclays as Fillers for Performance Enhancement in Building and Construction Industries: State of the Art and Future Trends

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Abstract

In construction engineering, there is currently a strong emphasis on finding construction materials, mainly the binder which plays a crucial role, that meet multiple criteria, including sustainability, cost-effectiveness, durability, and reduced environmental impact. However, there is a growing interest in exploring alternatives to traditional binders to address the limitations associated with their production and use. One such alternative is the use of naturally occurring materials like clay. Clay deposits are abundant and widely available, making them a sustainable resource for construction applications. Moreover, clay contains significant amounts of silica and alumina, which are key components for inducing pozzolanic reactions that contribute to the strength and durability of concrete. In recent studies, nanoclays (NCs) have emerged as a promising addition to construction materials as supplementary cementitious materials. These nanoparticles possess unique properties that can enhance the performance of concrete. Nanoclays significantly improve the compressive strength, sustainability, and durability of concrete structures. The high surface area and reactivity of nanoclays facilitate better bonding between cement particles, resulting in enhanced mechanical properties. This chapter aims to discuss the state of the art on performance enhancements of building materials that employ different types of nanoclays in place of conventional binders and the future trends.

Keywords: nanoclays, cement, bitumen, geopolymers, sustainable construction

1. Introduction

Clay is a natural, fine-grained mineral that hardens upon drying and plastic when moist, containing phyllosilicates and other substances that provide plasticity, along with additional phases and organic matter [1, 2]. Clay properties, including

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mineralogy and composition, are influenced by formation conditions, parent rock characteristics, and chemical transformations in volcanic ash [3, 4]. Clay minerals, originating from earth's crust and atmosphere, have unique characteristics like structure, fine particle size, and cation-exchange capacity, affecting water absorption, swelling, impermeability, and plasticity [5]. Clay, derived from the Greek word "argilos," is a fine-grained material with plasticity and hardening properties, formed through weathering, the breakdown, and chemical decomposition of igneous rocks [6]. Clay particles are formed through the long-term weathering and erosion of rocks containing soil, ceramic clays, clay shales, glacial clays, and significant amounts of detrital and transported clays [7, 8]. Clays and clay minerals form in various geological environments like soil horizons, sediments, geothermal fields, volcanic deposits, and weathering rock formations through physical breakdown and chemical transformation [9, 10]. Clays are extensively utilized in various industries, including refractory manufacturing, pottery/ceramic production, structural unit fabrication, and fillers or extenders in various products [11]. Ancient civilizations valued clay materials in construction, pottery, brick making, ceramics, paints, plastics, rubbers, cosmetics, and pharmaceuticals, as they enhanced the performance and properties of materials. **Figure 1** [3, 12, 13]: as depicted below shows formation of clays.

As shown in **Figure 2**, clay minerals are categorized by their chemical environment at the interface between rocks and the atmosphere, leading to destabilization and subsequent burial under high temperatures [14].

Clays are fine-grained 2D earthen minerals with a chemical composition of 60% silica and 15% alumina, with other mineral oxides in the remaining fraction [15]. Clay minerals in soil indicate site weathering and deposition history, providing insights into geological processes in residual soils originating from local rock [16].

In the field of soil mechanics, some of the key properties of clays include hydraulic conductivity, gas conductivity, ion diffusion capacity, swelling potential, compressibility, and rheological properties [17]. Clay minerals in soil indicate site weathering

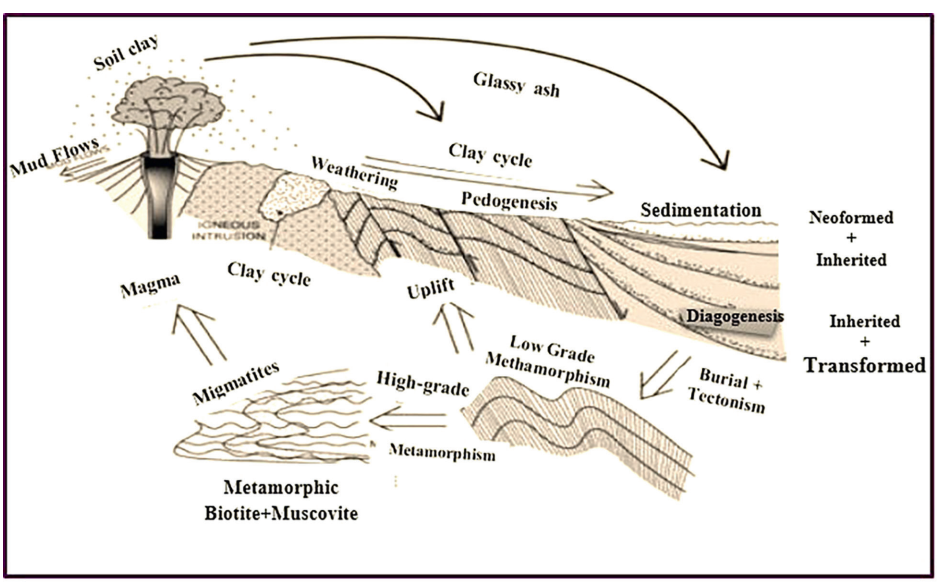

Figure 1.
Process of clay formation [3].

DOI: http://dx.doi.org/10.5772/intechopen.1005147

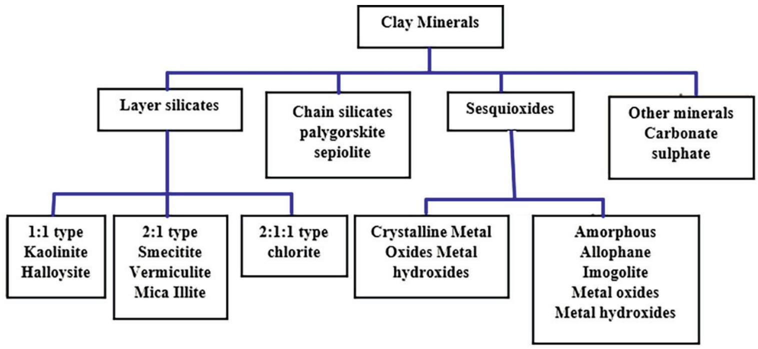

Figure 2.
Classification of clay minerals [7].

Primary properties	*Secondary properties*
Chemical composition	Granulometric composition
Density	Adsorptive capacity
Hardness	Specific density
Surface properties	Abrasiveness
Color	Precipitation behavior
Wettability	Rheological performance
Plasticity	Swelling capacity
Cation exchange capacity	Pore structure

Table 1.
Primary and secondary properties of clay [18].

and deposition history, providing insights into geological processes in residual soils originating from local rock [18]. **Table 1** as shown below provides a comprehensive overview of the primary and secondary properties associated with clay.

Clay nanoparticles are attracting interest due to their abundant natural availability, accessibility, effectiveness, and environmentally friendly characteristics. With a small grain size and unique crystal structure, they possess exceptional physicochemical properties such as a large specific surface area, surface charge, and cation exchange capacity [19, 20]. Clay minerals are layered silicates, composed of stacked aluminosilicate layers with high surface area, formed by fused tetrahedral and octahedral sheets and unshared oxygen atoms in hydroxyl form [21].

Research shows that the physical properties of modified cementitious materials are significantly influenced by factors like strength, porosity, mix composition, water content, specimen geometry, nanoparticle type, and age [22]. Consistency in cohesive soils is crucial for their strength, resistance to penetration, stability, and load-bearing capacity, influencing construction and geotechnical engineering practices [23]. The phyllosilicate structure's fundamental unit is an aluminosilicate layer consisting of a silica tetrahedral sheet and an alumina octahedral sheet, combined in specific proportions [24]. Nanoclay fillers like carbon nanotubes, graphene, nanocellulose, and nanosilica are renowned for their reinforcing properties, with clay being a notable filler due to its composition of layered silicates/clay minerals [25]. Nanotechnology enhances concrete properties by preventing cracks, reducing shrinkage, minimizing joint need, mitigating temperature curling, and reducing moisture loss warping [26]. Nano-sized silicon dioxide/nanosilica can enhance concrete properties by inhibiting water penetration, increasing density, and reducing environmental impact associated with concrete production and use [27]. Nanoparticles, including titanium dioxide, carbon nanotubes, silica, copper, clay, and aluminum oxide, have the potential to significantly improve the physical and chemical properties of construction materials [28]. Nanomaterials in bridges, composites, reservoirs, roads, and buildings offer benefits like reduced maintenance, thermal transfer, sound absorption, improved glass reflectivity, corrosion resistance, and lower life-cycle costs [29]. Nanosilica improves the interface between binding paste and concrete aggregates, enhancing mechanical strength, reducing water absorption, and sorptivity due to fewer capillary pores and pozzolanic activity [30].

Nanoparticles have been used in cement-based materials to enhance the performance and durability of the concrete [31]. Nanoclays, also known as layered silicates, are widely employed as nanofillers in the production of polymer layered silicate nanocomposites. Phyllosilicates (2:1), a type of layered silicate, are particularly favored and extensively utilized in the preparation of clay-based nanocomposites [32]. The incorporation of nanoclay into concrete has gained worldwide recognition in recent years, owing to its immense potential advantages and its growing significance within the construction sector. The attention given to clay minerals is justified by their abundance, accessibility, effectiveness, and ecological properties and have a unique crystal structure, are recyclable, easy to use, and possess remarkable physicochemical properties such as specific surface, surface charge, and cation-exchange capacity [33].

2. Synthesis and modification of nanoclays

2.1 Clay minerals

Clay, a hard earth material, can significantly alter the chemical and isotopic compositions of solid and fluid phases during weathering due to its unique layered structure and potency as an ion exchanger [34]. It consists of mainly fine particles of hydrous aluminum silicates and other minerals [35]. They can be found in many different types of habitats, including deep-sea sediments, lakes, estuaries, soils, weathering profiles, and hydrothermal systems [36]. Clays are typically made up of a diverse array of minerals, often mixed with other minerals and organic materials like feldspar, quartz, calcite, and organic matter [36–38]. Although these contaminants are important to the physicochemical characteristics of clays, their presence in high concentrations has a detrimental effect on clays' performance [3]. They are used in a number of industries such as biomedical [39], health care [40], construction [28, 41–44], environmental remediation, food packaging [45, 46], clothing and paints [47], soil fertility [48], etc. This chapter only focuses on the advancements of clay minerals (nanoclays) in construction industries.

2.2 Synthesis and modification of nanoclays

Nanoclay is a component of phyllosilicates, mainly defined by the presence of silicon, oxygen, and other elements. It comes from natural sources and has undergone subsequent chemical processing [48]. Nanoclay is made up of thin layers, each of which is between one and several nanometers thick and between several hundred and several thousand nanometers long [49]. There are a number of methods for synthesizing nanoclay, such as *in-situ* polymerization, melt-blending, and solution-blending [50]. The solution-blending approach is combining a polymer solution with nanoclay and then letting the solvent evaporate [51]. The melt-blending technique entails combining liquid polymer and nanoclay, then cooling and solidifying the mixture [52]. The *in-situ* polymerization method is the polymerization of monomers in the existence of nanoclay, leading to the formation of nanoclay-polymer composites [53]. Selecting the right synthesis approach for nanoclays depends on desired properties, such as scalability, cost-effectiveness, and compatibility with the polymer matrix.

Naturally occurring clay minerals include mixed cations on their surface and in the interlayer space, which makes their surface characteristics unsuitable for use in some applications [38]. To give clay minerals their unique physicochemical properties for definite purposes, their interlayer space is saturated with the required cations. The modification of clay particles can be done through (i) physical and (ii) chemical modification methods [54]. Physical modification of clay surface by modifying substances marginally improves polymer composite characteristics without altering clay structure due to minimal physical forces. Chemical modification of clay surfaces with tethered polymers or organo-silane compounds improves properties of polymer/clay nanocomposite systems, including improved dispersion, nano-sized layers, high aspect ratio, and large surface area [55]. Surface modification can be achieved by various methods, including acid treatment, surfactant treatment, and polymer grafting. Acid treatment involves the use of acid to remove impurities and increase the surface area of nanoclay [50]. Surfactant treatment involves the use of surfactants to modify the surface chemistry and improve the dispersion of nanoclay in polymers [56]. Polymer grafting involves the attachment of polymer chains to the surface of nanoclay, leading to improved compatibility with polymers [55, 57].

3. Structure and properties

Understanding the clay structure and its characteristics is crucial for comprehending the impact of clay reinforcement on the performance enhancement of construction and building materials. Nanoclays are layered mineral silicates composed of individual layers of octahedral ($[AlO_3(OH)_3]6$ or tetrahedral sheets $(SiO_4)4$ [58–60], stacking on top of one another like pages in a book [61]. In tetrahedral sheets, a silicon atom is surrounded by four oxygen atoms, and in octahedral sheets, a metal like magnesium or aluminum is surrounded by eight oxygen atoms, and are the building blocks of clay's layers. Tetrahedral (T) and octahedral (O) sheets are linked by oxygen atoms [3, 62, 63], while unshared oxygen atoms are present in hydroxyl form [62, 64, 65]. The octahedral sheet is formed by four apical oxygen atoms and two hydroxyl groups, with cavities occupied by trivalent or bivalent cations. Aluminum is typically used, and the structure is called di-octahedral when two cavities are trivalent cations. Tri-octahedral is formed when all cavities are divalent metal ions. Isomorphic substitutions can balance the charge deficit [3, 38, 62, 66–69]. In clay crystallite, multiple layers are joined by hydrogen bonds, Vander Waals force, and electrostatic force to form sheets, forming stacks of parallel lamellae [32, 61, 70]. Clay minerals consist of four structural types: three layered (1: 1, 2: 1, 2: 1: 1) and one fibrous structure (**Figure 3**) [3, 38, 62, 68, 71]. In 1:1 arrangements, the layer is

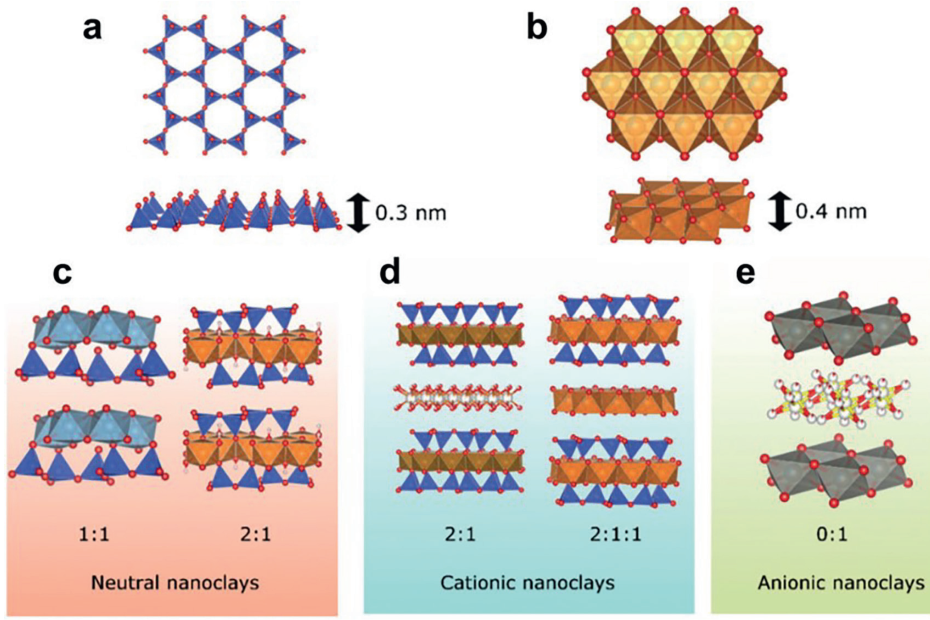

Figure 3.
Schematic representation of (a) tetrahedral, (b) octahedral sheet; (c) layered nanoclay 1: 1, and 2: 1 structures; (d) cationic nanoclays (types 2: 1 and 2: 1: 1), and (e) anionic nanoclay (type 0: 1) sheet arrangements in common nanoclay materials [68].

formed by one tetrahedral sheet linked to one octahedral sheet; in 2:1 arrangements, each octahedral sheet is connected to two tetrahedral sheets (one sheet on each side); and in 2:1:1 configurations, each octahedral sheet is adjacent to another octahedral sheet and connected to two tetrahedral sheets [64, 72]. Clay minerals with fibrous structure consist of ribbon-like layers of two tetrahedral sheets held together by a central octahedral sheet through shared oxygen; which results in a gutter-and-channel-type structure [73]. Depending on the arrangement of layers, bond types, chemical composition, and microscopic structure of the crystal lattice, there are different types of nanoclays, including montmorillonite, bentonite, kaolinite, hectorite, and halloysite nanoclay [74–76].

Kaolinite is a 1:1 type of clay mineral with a silica tetrahedral sheet connected to an alumina octahedral sheet connected by hydrogen atoms, with the chemical formula Al2Si2O5 (OH)4 [77–79]. The nanoclay of the kaolinite group has remarkable chemical and physical characteristics, including a high specific surface area, corrosion resistance, low density, and high thermal stability [79]. In natural kaolinite, Al^{3+} is replaced by Ca^{2+}, Mg^{2+}, or Fe^{2+}, while Si^{4+} is replaced by Al^{3+} or Fe^{3+}, resulting in an insufficient charge in the crystal lattice and a negatively charged surface [60]. Montmorillonite (MMT) nanoclay has a 2:1 structure with weak Van der Waals forces keeping the outer layers together, consisting of $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2{\cdot}nH_2O$ chemical composition [77, 80]. MMT, with its high aspect ratio, surface area, high cation-exchange capacities, and excellent mechanical properties, can swell up to several times its original size when exposed to water [48, 81]. Al^{3+} and Mg^{2+} are isomorphic replacements of Si^{4+} in the tetrahedral sheet and Al^{3+} in the octahedral sheet, respectively, to form the chemical compound known as MMT [59, 82]. Halloysite, similar to kaolinite in chemical composition, differs from kaolinite due to

Clay	Specific surface areas (m^2/g)	Cation exchange capacity (CEC) (meq/100 g)
Kaolinite	5-40	3-15
Halloysite (hydrated)	1100*	40-50
Illite	10-100	10-40
Smectites	40-800	80-120
Vermiculite	760*	100-150
Chlorite	10-55	10-40
Palygorskite-sepiolite	40-180	3-20
Allophane	2200	30-135
Imogolite	1540	20-30

**depending on the fraction of internal specific surface area.*

Table 2.
Cation-exchange capacities and specific surface areas of clay minerals [38, 86].

its unique structure consisting of a single water molecule layer with chemical composition $Al_2Si_2O_5(OH)_4.nH_2O)$ [79]. Halloysite is characterized by 15-20 thick layers, forming a hollow and porous tubular structure with hydrophilic and negative charges, strong adsorption, high specific surface area, water dispersion, biocompatibility, and active surface chemical [79, 83]. Some of the better-known members of the clay family have the following chemical formula: talc ($Mg_3[Si_4O_{10}(OH)_2]$), mica($KA_{12}[Al Si_3O_{10}(OH)_2]$), serpentine, ($Mg_3[Si_2O_5(OH)_4]$), sepiolite($Mg4[Si_6O_{15}]$ $(OH)_2.4H_2O$) [68, 84]. The chemical composition of nanoclays may be different, including the aluminum silicates, magnesium silicates, aluminum–magnesium silicates, and other mineral silicate nanoforms [85]. **Table 2** depicted the cation-exchange capacities and specific surface areas of clay minerals [38, 86].

4. Nanoclays for the performance enhancement in building and construction materials

4.1 Mechanical properties

4.1.1 Nanoclays in concrete and asphalt binders

Various types of nanomaterials (such as nano-silica, carbon nanotubes, nano-titanium dioxide, nano-alumina, nanoclay, nano-zinc oxide,) are employed to enhance the strength, durability, and overall physical and chemical properties of concrete [87]. The use of nanoparticles in construction enables more cost-effective, time-efficient, and safer production of construction materials, resulting in enhanced product durability, efficiency, and higher performance levels in the production of raw materials [88]. The incorporation of different nanoparticles into concrete at appropriate concentrations has the potential to enhance its mechanical strength and chemical durability, and reduce shrinkage, while also minimizing issues such as bleeding and segregation [89]. The introduction of nano-sized particles fills the interfacial transition zone between cement and aggregate, leading to densification of the cement matrix by enhancing the formation of calcium-silicate-hydrate (C-S-H) gel through the pozzolanic reaction with calcium hydroxide [90]. Nano particles also have the capability to enhance the bond between aggregates and cement paste [91]. Nanoparticles are highly effective additives for modifying cement products, even when used at low concentrations of approximately 1% [92]. Another research [93] demonstrated that nanoclay admixture improved the compressive property of cement calcareous sand (CCS) with an optimum admixture ratio of 8%, enhanced the deformation modulus and resistance to external load deformation, and increased the density of the internal structure, thereby improving the mechanical properties of CCS.

In the pavement industry, natural nanoclays, particularly montmorillonite, hectorite, saponite, and kaolinite, are commonly used, while organically modified montmorillonite known as Cloisite is utilized as an asphalt modifier [94]. Cloisite-modified asphalt mixture, nano clay modification was found to enhance the mechanical properties, including creep resistance, tensile strength, and fatigue resistance, effectively improving the performance of the polymer as a filler reinforcement [95]. The utilization of nanomaterials in the construction industry holds immense potential for enhancing the performance and properties of building materials [96]. The high aspect ratio and large specific surface area of nanoclays contribute to improved load transfer, enhanced interfacial bonding, increased resistance against cracking, improved flexural and compressive strength, and enhanced impact resistance [97]. Nanoclays, offer a promising alternative to traditional additives, providing exceptional mechanical properties and unique geometrical characteristics. Their precise distribution fills nano-sized voids in cement mortar, limiting micro-crack propagation and improving strength, workability, consistency, and water absorption [98]. The incorporation of nanoclay into concrete has several beneficial effects, including reducing building energy consumption, enhancing thermal insulation properties, improving thermal stability, fire resistance, thermal performance, behavior, resistance to cracking and degradation, and decreasing thermal conductivity, which leads to effective insulation and lower energy consumption during heating and cooling periods [33]. Nanoparticles contribute to the development of strength in cement-based materials by enhancing the hydration process of cement, resulting in the formation of calcium-silica-hydrate (C-S-H) and improved overall strength [99].

4.1.2 Nanclays in polymer composites

Nano-particles are currently recognized as highly promising fillers for enhancing the mechanical and physical properties of composite materials [100]. The incorporation of hydrophilic clay minerals into hydrophobic polymers can enhance their mechanical performance, fire retardant, and barrier resistance, as well as their thermal and electrical conductivities [101]. Adding nanoclay particles below or above their optimum point reduces material performance by introducing voids that act as preferential locations for crack initiation and failure [102]. Nanoclay particles are currently recognized as promising fillers for improving the mechanical and physical properties of polymers [103]. The addition of fillers to polymer matrices provides an alternative approach to enhance the mechanical performance, processability, and cost-effectiveness of composites as well as reduces available free spaces, resulting in increased stiffness of the laminates and improved interaction between the fibers and the matrix [104]. According to the study [105], the experimental evidence demonstrates that increasing the weight percentage of nanoclay in Coccinia Indica fiber reinforced epoxy composites enhances their tensile, flexural, impact, and compression properties. The results found in [106] reveal that Polymethylmethacrylate nanocomposites with a minimal loading of 0.5 wt% well-dispersed montmorillonite nanoclay, significant enhancements were observed in the mechanical properties of the nanocomposites, including improvements in elastic modulus, tensile strength, and elongation at break. Based on the study conducted by [107], the incorporation of nanoclay particles in composite films resulted in a significant improvement in flexural modulus, especially at lower weight percentages.

Recent research, as referenced in [32], have documented that the fabrication and characterization of nanoclay-based nanocomposites and bio-nanocomposites, exhibited superior mechanical and thermal properties when compared to nanoclay-reinforced polymer composites. The incorporation of layered silicates into polymer nanocomposites leads to notable improvements in their mechanical properties, including modulus, strength, toughness, and strain [108]. Nanoparticles enhance the properties of many polymers and are used to improve modulus, tensile strength, flame resistance (to further improve the flame retardant performance), and thermal and structural properties in various applications [109]. Nanoparticles can serve as heterogeneous nuclei in cement pastes, effectively accelerating cement hydration due to their high reactivity. They also act as nano-reinforcements and nano-fillers, leading to densification of the microstructure and reducing porosity in cement-based materials [110]. As mentioned in the study referenced [111], incorporating nanoclay into the cementitious mixture for 3D printing concrete resulted in a decrease in workability but an increase in the yield stress due to enhanced cohesiveness. Increasing the amount of nanoclay not only maintained the desired shape during and after extrusion but also improved layer stability, preventing collapse under the weight of subsequent layers. Another finding reported in Ref. [112], is the successful incorporation of clay into various industries, including transportation, construction, packaging, and medical sectors, offers improved mechanical properties and enhanced functional characteristics such as fire retardancy, ablation performance, and gas permeability. In another study [113], it was observed that the addition of nanoclay to epoxy resin resulted in a significant increase in the elastic modulus and fracture toughness. However, as the nanoclay level increased, there was a notable reduction in the failure strength and failure strain. In line with the conclusions drawn in Ref. [114], the addition of a small amount of organoclay, around 4 wt%, to polymers leads to significant improvements in barrier properties, dimensional stability, flame retardant, mechanical properties such as tensile strength, Young's modulus, and flexural modulus this allows for the creation of lighter and more transparent composites.

The study outlined in Ref. [115], highlights that nanoparticles-reinforced polymer composites, particularly montmorillonite/epoxy nanocomposites, have undergone thorough investigation and have shown substantial improvements in mechanical, thermal, and physical properties. The incorporation of nanoclay into composites significantly enhances the mechanical properties (tensile strength, flexural strength, compression strength, and impact resistance) thermal stability, and flame-retardant characteristics [116]. Nanomaterials aim to enhance mechanical and physical properties at the nanoscale, improving durability [13]. The incorporation of clay in nanocomposites leads to significant enhancements in interfacial interactions with the matrix and physical properties. Based on the findings obtained in Ref. [101], the results indicate that the mechanical properties of the composites improved with an increase in filler content, and the optimum mechanical properties in percentage were found to be 4%.

Incorporating an appropriate amount of clay content into materials has been found to enhance several key properties, including tensile strength, modulus (stiffness), thermal stability, elasticity, and heat deflection temperature [117]. The incorporation of filler nanoparticles in the resin matrix of dental composites enhances their esthetic, optical, and mechanical characteristics, including factors like tensile strength, fracture resistance, and reduced polymerization shrinkage [118]. Based on the findings reported by [119], it was concluded that the addition of fillers increased the stiffness of the polymer composite. However, when the filler ratio was increased beyond a certain point, particle agglomeration occurred, leading to decreased adhesion between the matrix and fillers, resulting in a decline in the mechanical strength of the composite [119].

4.2 Thermal properties

4.2.1 Nanoclay in modification of concrete

The thermal response of concrete is crucial in construction industries. This property can be altered by using different additives which can give thermal stability to the concrete. Researchers have investigated the effect of nanoclays on the thermal stability of concrete [120–124]. Hakamy et al. [125] carried out the thermal stability of nanoclay (Cloisite 30B) and calcined nanoclay-cement nanocomposites. They found that thermal stability was improved by 3.3% compared to the control cement paste and also showed that adding Cloisite 30B nanoclay reduced the weight loss of cement mortar. The thermal stability of hemp fabric-reinforced nanoclay-cement was also investigated in another work [122]. The study found that adding nanoclay to hemp fibers-reinforced nanocomposites increased their thermal stability, as revealed by thermogravimetric analysis. The thermal behavior of cement mortar treated with kaolinite nanoclay was studied by Fan et al. [126]. According to their DTA data, the specimens' weight loss was decreased by 5% when nanoclay was added, which resulted in exceptional heat stability and resistance to heat. Mohammad and Mohammed [123] investigated the thermal performance and fire resistance of nanoclay-modified cementitious materials using montmorillonite nanoclay as partial replacement for cement. The addition of nanoclay significantly reduced the degradation in the tensile and flexural strengths of cement mortar due to elevated temperature exposure. Research work [121] also demonstrated that partial replacement of cement up to 3%wt. could reduce the thermal conductivity of the concrete considerably.

4.2.2 Nanoclay in modification of polymers

Polymers have many more uses besides concrete, prefabricated structural elements, and strengthening elements. Some of these include pipeline sheaths, plastic films, decorative panels, floors, doors, windows, and sanitary facilities. [127]. The addition of nanoclay fillers in polymer matrix have great effect in improving the thermal properties. High density polyethylene (HDPE), one of the polymer used in construction industries, can be modified with nanocomposites produced industrially by melt mixing approach [128]. Harun et al. [128] modified HDPE with nanoclay reinforcement, enhancing mechanical and thermal properties, resulting in increased glass transition temperature and decreased Vicat softening temperature. Based on exfoliated organoclay polystyrene and poly(methyl methacrylate) (PMMA), a study [129] assessed the thermal characteristics of nano montmorillonite. TGA analysis and calcination reveal that nanoclay addition enhances thermal stability in organoclay polymers, with a rise in degradation temperature of 25-50°C above neat PS and 25-80°C above neat PMMA.

4.2.3 Nanoclay in modification of asphaltic bitumen

Improvements in the pavement sector, including heavy axle design, traffic leveling, huge truckloads, and environmental requirements, necessitated the need for asphalt binders to be improved [130]. Polymer modification has become increasingly popular in recent decades as a means of enhancing asphalt pavement's high-temperature performance [131] without compromising its low-temperature behavior. One of the technique to improve high-temperature performance is using nanoclays as a reinforcement [130, 132, 133]. Atefeh et al. [134] tried to modify bitumen by ethylene propylene diene monomer (EPDM) blended with hybrid nanoparticles (carbon nanotubes (CNTs) master batch and bentonite nanoclay) to improve thermal and other properties. Thermogravimetric measurements showed that the hybrid samples significantly improved bitumen's viscoelastic behavior at high temperatures by adding minimal amounts of additives. Bahadır et al. [135] assess the thermal properties of nanoclay-modified bitumen using organo- montmorillonite nanoclay. In the DSC result the glass transition temperature of modified bitumen has increased with the application of nanoclays. Moreover, the use of nanoclay in bitumen has turned exothermic process of bitumen melting and crystallization into endothermic. The viscosity of the material at elevated temperatures surpasses that of the original binder, indicating greater resistance against permanent deformations.

4.2.4 Nanoclay in modification of geopolymer

Assaedi et al. [136] utilized nanoclay platelets (Cloisite 30B) for the mechanical and thermal properties improvements of fly ash geopolymer. The thermal stability of samples was determined using TGA. In this test, the thermal stability was studied in terms of the weight loss percentage as a function of temperature in Argon atmosphere. The neat geopolymer exhibits significant porosity, reducing water capacity, but the sample with 2% NC shows the highest thermal stability, with a nanocomposite peak slightly higher than other samples. Khater et al. [137] investigated the effect of nanoclay on alkali-activated water-cooled slag geopolymer. Kaolin nanoclay, prepared through firing at 800°C, was added to geopolymer with a 0 to 7% dry weight ratio, increasing the ratio of nanoclay from 1 to 1.5% improving thermal and thermal insulation qualities.

4.3 Rheological properties

4.3.1 Nanoclay in mofication of concretes

Rheology describes how a material deforms and flows when applied stresses and shear rates are applied. The flow curves that relate yield stress, shear rate, and plastic viscosity provide a better explanation for the flowability of fresh concrete [138]. Over the past few decades, it has been thoroughly investigated in cement-based materials, leading to the establishment of several analysis approaches. Nanoclays are widely considered to require minimal pre-dispersion in concrete production due to their ease of dispersion under shearing by conventional mixing [139]. Small amounts of nanoclay (less than 1% by binder weight) increase the green strength of self-associating concrete immediately after casting without significantly altering flowability [140, 141]. Dejaeghere et al. [140] studied the impact of nanoclays on the rheological properties of cement-based mortars. The outcome demonstrates that the card-house-like microstructure created by the extremely small, strong nanoclay particles raised the static yield stress. A study [141] on shear rheology revealed that nanoclays have minimal long-term effects and an instant stiffening effect controlled by flocculation, rather than water adsorption. The research [142] on Self-Compacting Concrete (SCC) utilized nanoclays attapulgite, bentonite, and sepiolite NC, and found that sepiolites significantly impacted the rheological characteristics of fluid cement pastes.

Figure 4a illustrates the stress development of fresh cement pastes under 0.01 s^{-1}. It is evident that stress first rises more quickly before slowing down and eventually leveling out. Before the flow begins, the peak value is linked to static yield stress. **Figure 4b** illustrates the cement paste storage modulus within the linear viscoelastic region (LVR) following the addition of nanoclay. With the addition of nanoclay, the storage modulus G' rises from 2.96×10^4 to $1.72\ 10^5$ Pa [143]. In general, nanomaterials reduce the amount of free water in mixture, which lowers the fluidity or flowability and negatively impacts workability [142].

4.3.2 Nanoclay in modification of polymers

Petroleum-based polymers are not compatible with nanoclay materials due to surface energies differences, requiring surfactants to reduce clay layers' surface energy [45]. Karami et al. [144] studied the impact of microstructure on the rheology of blends of LDPE and polyhydroxy butyrate (PHB) filled with nanoclay and **Figure 5** displays the complicated viscosities of the matching nanocomposites and the neat PHB and LDPE. As shown in **Figure 5**, adding more nanoclay in place of PHB, the complex viscosity would increase significantly. Kolahchi and Kontopoulou [145] found that the neat PHB exhibited a very low viscosity and a Newtonian plateau with minimal shear thinning. The PHB nanocomposite exhibited increased shear thinning behavior with increased addition of Cloisite 10A organoclay, indicating a higher affinity for this material (PHB) [146]. The addition of nanoclay to PHB75/LDPE/N5 or PHB/N5 enhances its elasticity and melt viscosity, thereby improving its processability. Pan et al. [147] found that nanoclay composites significantly improved the resistivity and rheological properties of synthetic-based drilling fluids for high-temperature applications.

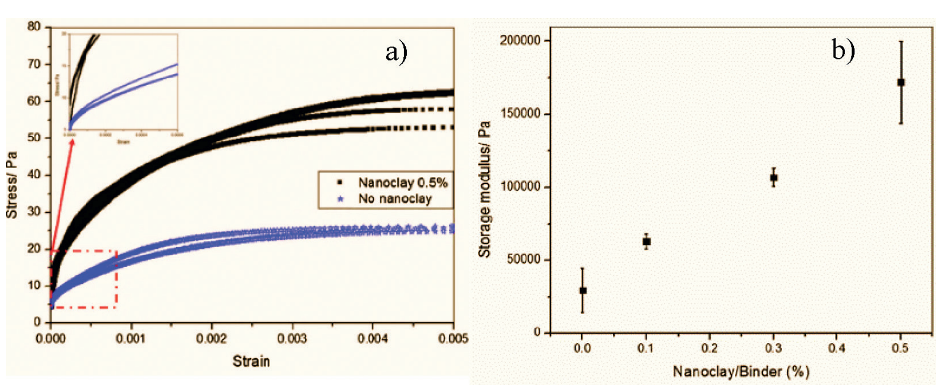

Figure 4.
(a) Stress development of cement pastes without and with 0.5% of nanoclay addition under 0.01 s^{-1} and (b) storage modulus of cement pastes with various nanoclay addition [143].

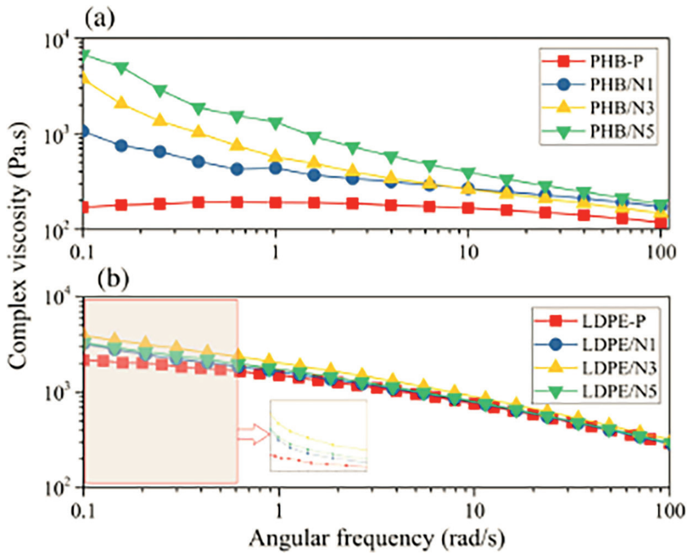

Figure 5.
Complex viscosity as a function of angular frequency for PHB and LDPE nanocomposites (composition, PHB-P, pure, PHB/N1:100/1, PHB/N3:100/3, PHB/N3: 100/5 and similar representation for LDPE) [145].

4.3.3 Nanoclays in modification of asphaltic binder

Nanoclay composites are used in a number of novel applications, such as in asphalt mixtures, where they improve the rutting and fatigue resistance of asphalt mixtures, and enhance the storage stability and the aging resistance of polymer-modified asphalt mixtures [146]. Many research works reported that nanoclays improve the rutting resistance of asphaltic binder [130, 148–152]. Shah and Mir [153] found that combining kaolinite clay and styrene-butadiene-styrene (KC/SBS) in asphalt improves compatibility with SBS, enhancing performance of rutting strength. Amini et al. [148] modified asphalt rubber binder (ARB) with nanoclay to enhance rutting resistance, fatigue properties, and temperature susceptibility. Nanoclay addition improves ARB's performance, reduces viscosity-temperature susceptibility, and temperature susceptibility, while decreasing permanent strain, enhancing rutting resistance, and improving elastic recovery. Another important parameter in asphaltic binder is fatigue resistance which simulates repeated loading cycles of vehicle on pavement road. The role of nanoclay in fatigue resistance of asphaltic binder has been researched extensively [154–157]. Saboo et al. [152] performed the effect of nanoclay on physical and rheological properties of waste cooking oil–modified asphalt binder. The result of the study indicated that addition of nanoclay to WCO-modified asphalt binders improves the physical and rheological properties. The integration of nanotechnology and polymer science can significantly improve the production of modified asphalt mixtures for improved road performance. This alternative has significant potential to improve asphalt surfaces, especially in tropical countries and slow, heavy traffic highways to reduce rutting [150].

4.3.4 Nanoclay in modification of geopolymers

Geopolymer is a three-dimensional polymer having various types of amorphous and semi-crystalline phases with a linkage of Si–O–Al [158]. To produce cellular geopolymer, a stable bubble structure has to be created within an alkali-activated fly ash (AAF) binder paste, which on hardening produces a solid geopolymer matrix and an entrained pore structure [159]. Nanoclays made of montmorillonite and bentonite minerals were used as rheology modifiers. Bentonite typically produces a thickening effect at low concentrations without increasing the elastic response. Montmorillonite has been used as a thixotropic agent in alkali-metal silicates [160]. The result of Gadkar A, Subramaniam KVL [159] confirmed the yield stress of AAF binder pastes is increased with the addition of nanoclay. Montmorillonite is more effective than bentonite in increasing the yield stress of AAF binder paste. A similar increase in the yield stress is obtained at a larger dosage of bentonite.

4.4 Barrier and moisture resistance properties

Nowadays, nanoclays are one of the most widely used nanoparticles in the field of construction and building industries, since they have the potential to enhance the flame retardance, thermal, mechanical, chemical, and barrier properties of building and construction materials [161, 162]. Researchers have investigated the effect of nanoclays on the barrier, chemical and moisture resistance properties of building and construction materials [163–167]. Kim et al. [164] study on organoclay-epoxy nanocomposites revealed that water absorption behavior is influenced by factors like matrix and fiber properties, interfacial adhesion, and voids. The hydrophilic nature of natural fiber-reinforced polymer composites, particularly B/K/Epoxy (11.4%), is the primary driver for water absorption, making it the most water-absorbing composite. **Table 3** illustrates that, out of all the hybrid nanocomposites, B/K/OMMT had the lowest water absorption, with a value of 4.19%. For B/K/MMT and B/K/HNT, the corresponding percentages of water absorption are 4.99 and 5.12%. Because of their hydroxyl groups, natural fibers, especially cellulose and hemicellulose, absorb water [164]. Hybrid nanocomposites can suppress water absorption by adding nanoclay, which reduces void content, creates a moisture barrier, and limits polymer chain motions and relaxation [164, 168]. Ola Bakr Shalby et al.'s [169] study shows that using nanoclay alone as a partial cement replacement reduces water penetration depth from 15 to 9 cm, while the proposed NCSF mix only improves it to 12 cm due to irregular steel fiber shape [169]. Calambas et al. [170] found that adding more than 0.5% MMT to polymeric achira starch/PVA formulations significantly increases the water vapor transmission rate, reducing the materials' barrier capability. The addition of montmorillonite nanoclay to biopolymers-clay nanocomposites altered their water-barrier properties due to their inherent properties. However, sonication of MMT nanoclay is crucial for improving properties, as films with sonicated MMT nanoclay exhibit better wettability and absorbency.

Composites	Maximum moisture content at saturation point, M_∞ (%)	Diffusion coefficient, D($\times 10^{-6}$ mm^2/s)
B/K/Epoxy	11.4	1.99
B/K/MMT	4.99	1.26
B/K/HNT	5.12	1.34
B/K/OMMT	4.19	1.19

Table 3.
Maximum moisture content at saturation point and diffusion coefficient of the hybrid composites/nanocomposite [164].

Alimohammad et al. [171] found that adding nanoclay to concrete reduced chloride diffusion coefficient, with the lowest coefficient observed on concrete with 3% nanoclay. After 90 days, the electrical resistivity increased, with 1, 2, and 3% mixes showing a visible decrease in initial current due to lower permeability. Niu et al. [172] found that the addition of nanoclay can improve the concrete's resistance to chloride penetration, as per their observation. The study by [173] found that nanoclay enhances resistance against moisture damage in hot mix asphalt, with 6% of nanoclay showing the most significant improvement in moisture susceptibility (**Figure 6**).

The study by [175] examined the impact of nano-based coatings on concrete under heightened exposures, revealing that the addition of nanoclay significantly impacts the chloride content in the concrete. The addition of nanoclay to reinforcement concrete increased chlorine content from 25 to 49%, enhancing its anticorrosion properties and lowering the rebar corrosion ratio by 7, 30, and 37% after 24 hours with the 1, 3, and 5% nanoclay addition, respectively. Woo et al. [176] found that concrete without coating had the highest chloride content, but coatings like neat silane and nanocomposite significantly reduced it by 92 and 69%, respectively. It was observed by [177] that the chloride diffusion coefficient of cement concrete decreases exponentially with the addition of clay. The study found that adding kaolinite clay to cement concrete reduced the chloride diffusion coefficient to 8.68 and 18.87%, indicating that increasing clay content leads to a reduction in the coefficient.

Li et al. [165] found that organo-montmorillonite nanoclay effectively inhibited bitumen's volatile organic compounds (VOCs) emission, with nanoclay containing octadecyl trimethyl ammonium surfactants showing better inhibition. Umk et al. [178] found that adding nanoclay to water-based coatings increased adhesion and mechanical properties, with 2% being the optimal percentage, despite some adverse effects. The study by [179] found that nanomaterials reduced water absorption ratios and chloride diffusion coefficients in coated concrete. The 0.5% nano-SiO2 polymer-modified cementitious coating showed lower chloride diffusion coefficients, especially at 200 days, indicating higher improvement efficacy in chloride resistance compared to 0.5% nano-TiO2. Abuzeid et al. [167] found that nanoparticles in concrete coatings improve resistance against physical salt attack and salt-frost exposure, but higher nanoclay dosages resulted in inferior performance. Usman et al. [180] studied the bitumen modified with nanoclay/pet(polyethylene terephthalate) blend properties, and noted that penetration decreases with replacement, with optimal values at P0.5% - N1.0% (65.0 mm) and P1.0% - N2.0% (65.4 mm). This is due to, PET

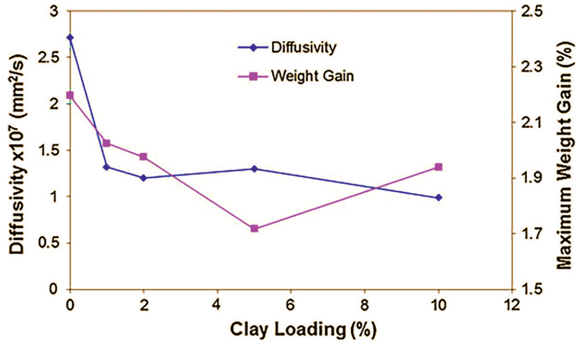

Figure 6.
Variation of diffusivity and maximum weight gain with nanoclay loading. (adapted from Ref. [174]).

absorbing low molecular components of bitumen, causing swelling and movement restriction within asphalt, resulting in reduced penetration of the modified bitumen.

4.5 Fire retardancy

The heating process causes changes in the microstructure of building and construction industry, which in turn affects the structural characteristics of the material [181, 182]. Structures may be efficiently protected by combining passive and active fire prevention systems with management systems like smoke exhaust systems and communication protocols [22, 183]. Researchers are promoting the use of nano-materials as additives to improve thermal resistance in cementitious composites, as they offer superior reactivity compared to micro-scale materials, preventing structural failure [184, 185]. Recently, owing to their smaller particle size than cement grains, nanoclays, such as nano-kaolin, bentonite, mica, and nano-montmorillonite, are utilized as nanofillers in cement-based products which improve chemical, moisture and gas barrier, and mechanical and thermal properties of the material [186]. Nguyen et al. [187] found that the combustion rate (mm/min) of epoxy resin/nanoclay/multiwalled carbon nanotube nanocomposites decreased from 28.41 to 20.80, while the LOI (vol. % O2) increased from 20.6 to 24.6. The addition of nanoclays increased the UL94 from not rated to 18.76 HB. The nanoclay components create a barrier-like substance, slowing down oxygen flow and preventing flammable elements from burning. However, improper dispersion can lead to residual nanoparticles reducing the materials' mechanical properties and fire resistance. Mahesh et al. [188] found that nanoclay addition to vinylester/carbon specimens reduced burning rates by 38 and 46%, respectively, indicating that MMT acts as a good flame retardant, reducing flammability. The improvement in fire behavior is due to the formation of a surface layer during pyrolysis that acts as a heat barrier, preventing heat transfer and increasing surface radiation heat losses [189]. Fillers within the polymer matrix offer a protective clay-rich barrier, thereby reducing the polymer's mass loss rate (MLR) [181, 190–194]. Saraeian et al. [195] investigate the effect of nanoclay particles on the tensile strength and flame retardancy of polystyrene – nanoclay composite. The study showed that adding 5% clay to polystyrene-clay nanocomposite significantly reduced its heat release rate, resulting in a flammability decrease of over 70%, with tests conducted on three nanocomposite groups. Ji & Li [196] found that adding 1.0 wt.% nanoclay to a fire test can reduce mass loss by nearly 13%. The nanoclay morphology transitioned from discontinuous intercalated to well disperse and continued exfoliated, forming insulated layers and a thick charring layer, which partially or completely halted chemical reactions.

Rajaei et al. [197] found that adding 2 wt. % halloysite nano-tube to epoxy slightly reduced the peak heat release rate (PHRR) by about 17%, while incorporating layered double hydroxide (LDH) significantly decreased the PHRR by around 58%. LDH nanoparticles can form a ceramic-like char on the sample's surface, shielding it from heat and flame, but no change in PHRRs was observed with increasing LDH content. The result also shows that adding 18 weight percent APP to EP2LDH and EP2HNT samples reduced PHRRs by 70 and 84%, respectively. Layered nanoclays such as LDH and MMT mitigate the flammability of polymer nanocomposites [198, 199], whilst fibrous nano-additives like carbon nanotube and HNT provide excellent thermal stability which facilitates the formation of chars [199, 200]. Usman et al. [180] studied on properties of bitumen modified with nanoclay/pet (polyethylene terephthalate) blend, and noted that the modified bitumen fire point values were less than the unmodified bitumen (control bitumen). This is due to the strong interfacial interaction between bitumen and nanoclay. Nanoclay shields bitumen from thermo-oxidation due to its "labyrinth" effect, forming a carbonaceous silicate structure that delays volatile product escape and oxygen penetration.

5. Sustainability and environmental considerations

Population growth has caused expansion of cities and, as a result, an increase in the demand for construction and building. On the other hand, excessive use of non-renewable resources, water, and materials, and non-neutrality of emissions are the major challenges facing the sector. This resulted in depletion of natural resources and pollution which are ever-existing problems and increasing at an alarming rate. The building and construction industries are the major consumers of global energy and significant contributors to environmental pollution. It has been identified that the construction and building sector is currently responsible for 40% of solids generation, 36% of global energy demand, 12% of drinking water depletion, 37% of energy-related CO_2 emissions, and 38% of greenhouse gas emissions [201]. Concrete manufacturing, the second most consumed material in the world next to water, is single-handedly responsible for 8% of anthropogenic CO_2 emissions, which results mainly from the Ordinary Portland Cement (OPC) manufacturing used as a binder [202]. Manufacturing of Ordinary Portland Cement (OPC) in particular accounts for 5–8% (roughly 1.35 billion tons of carbon dioxide per year) of greenhouse gas emissions worldwide due to the extensive amount of thermal energy used, which is mainly derived from non-renewable resources such as natural gas, coal, and others [203–208]. Furthermore, research on emissions analysis demonstrated that there is a one-to-one relationship between cement output and CO_2 emissions, which is frightening for the future of human beings [209]. This is further amplified in such a way that it is predicted that the annual global output of cement will reach to 6.1 billion tons by 2050 [210, 211]. Moreover, the use of cement-based concrete as the primary building material is expected to continue to increase to meet the rising need in the construction sector, with a yearly growth rate of 5% in cement production [212, 213]. Continuous repair of damaged buildings from conventional concretes synthesized from OPC, which is labor intensive and expensive process and a concern for environmental mitigation, has also continued to be the challenge for the sector [212]. Therefore, developing more sustainable and environmentally benign concrete mixture options is highly anticipated to lower environmental impacts related to the construction industry. Fortunately, recent developments in green construction are gaining emphasis and are becoming the global agenda for academicians and policymakers [214]. Significant efforts have been put into effect by researchers and industrialists to explore innovative approaches to enhance the performance of construction and building materials and to reduce their environmental impacts. These developments aim to reduce the reliance on cement-based construction in order to minimize carbon dioxide emissions which consequently provide significant environmental benefits. In this regard, geopolymers, ecologically benign cementitious ingredients requiring less energy and producing less CO_2, have emerged as potential alternatives to traditional cement-based construction materials with better performances in compressive strength, acid resistance, creep, and shrinkage [215–219]. Furthermore, the cementitious materials used to produce geopolymers are derived from industrial wastes including slag [220], fly ash [221], and waste glass powder [222]. However, high porosity, poor interfacial bond strength, and delayed strength gain at a later stage in geopolymer-based construction materials, like geopolymer concrete, deter its performance and industrial applications.

Nanoparticles are materials with new insights recently considered outstanding filler materials to alleviate the challenges in geopolymer concrete [223–225]. Geopolymer concrete performance can be improved by incorporating nanoclays, nanoparticles with unique properties, into the mix, and have been considered as a promising solution for the building and construction sector. Environmental and economic benefits of nanoclays, such as their excellent compatibility with water-based systems reducing the need for harmful solvents and volatile organic compounds, and their renewability, have recently created sizable interest in nanoclay-based composites. Research showed that incorporating nanoclays into the geopolymer paste increased the water volume used, consequently lowering the setting time and improving solidity of the paste [226–229], which resulted improvements in self-compaction, ductility, durability, weight reduction, air quality, resistance to chloride penetration, reduction in water and oxygen permeability, lessening in shrinkage, increase in the mechanical strength, and resistance to chemical solvents of the concrete [88, 230]. Optimization in the amount of nanoclays used in the mix determines the best performance; adding a higher percentage may diminish the performance, which is caused by the agglomeration of the nanoparticles [231]. The addition of proper amount of nanoclays to the cementitious mix may lead to synthesis of a new material with improved performances in mechanical properties with significant gains in economic, social, and environmental aspects. As a technical solution to augment properties of concrete, the integration of nanoparticles in concrete mixes has recently promoted and emphasis has been given to the investigation of the effects of the nanoparticles on performance of the composite material.

On the other hand, the use of geopolymer concrete in the construction industry is still in its infant stage. There is no general consensus regarding the influence of nanoparticle additives on the original material, the optimum dosage, or the synergistic effects of the mix components. There is no clear understanding of the mechanism of dispersion, diffusion manner, the hydration process, the chemical reactions at nanoscale, hardening process, overall performance assessment, ease of operation, and others. Particularly, the balance between operational ease and uniform dispersion of nanoparticles presents major challenges in commercialization of nanoclay-reinforced geopolymer concrete in the construction industry. Besides, there have been observations also that the hardening temperature increases with the addition of nanoclays [125]. Additionally, variations in the results of research outputs on the effects of nanoclays on concrete or cement mortar are usually observed due to changes in the type (fly ash, silica fume, etc.) used in the mix and differences in the curing days [201]. Therefore, the behavior of naoclay-reinforced geopolymer concrete is still an active research area for further exploration. Further studies are also needed to develop predictive models to evaluate the correlations between nanoclay particles and the performance enhancements in the geopolymer construction materials; this significantly increases the efficacy of the process and minimizes material wastage.

Despite the gains in environmental impact reduction by using nanoclay-embedded construction materials, the synthesis of the nanoparticles is highly energy-intensive and the process is not yet optimized, which is mainly researched at lab or pilot scale. Inhaling or ingesting high doses of nanoparticles during processing of the mix may cause health effects for construction workers. Hence, studies on the cradle-to-gate life cycle assessment of the nanoparticles showed an increase in other impact categories such as potential ecotoxicity and toxicity [201]. Thus, investigations regarding the environmental impacts of nanoclays addition to mixed designs of construction and building materials are not still sufficient and require further emphasis. Likewise, there are still concerns about the sustainability of concrete structures built from nanoparticle-enabled materials. Environmentally safe and sustainable applications of such materials are demands in prospect for the construction and building industries.

6. Challenges and future perspectives

6.1 Challenges

The absence of consistent dispersion of nanoparticles, which agglomerate in cement, presents difficulties for the building sector [232]. However, the improved hydrophobicity and self-attraction of carbon nanotubes and carbon nanofibers make their application desirable. It is essential to comprehend intricate systems and interface interactions [233]. Ingredients could require further steps, such as purification and functionalization, before they are combined. Nevertheless, this can lead to a weak link forming between the cement and the nanomaterials (carbon nanotubes and carbon nanofibers). Some scientists have created a simple technique to enhance the dispersion of carbon-based nanomaterials in an attempt to tackle this issue.

Since clay-based nanomaterials are hydrophilic, extra caution must be used to regulate the amount of water required in the clay-cement composite. Exchange alteration lowers the hydrophilicity of the interlayer by substituting an organic cation for any calcium or sodium that may have been present. This results in a reduction in water. The main issue to take into account when using nano-coatings on some cultural heritage stones was their photo-induced super hydrophilicity, which could have a negative effect on the stone [234].

Another obstacle to the widespread application of nanoparticles is their compatibility with building materials [235, 236]. In relation to titanium dioxide nanoparticles in particular, some studies have confirmed that there may be more complications when titanium dioxide is added to cement as opposed to coating other substrates like ceramics and glass. Cement has a lower surface area and poor stability [237, 238], which are detrimental to the photocatalytic reaction and have an adverse influence on the use of low stability in building matrices. Its efficiency decreases over time. Generally, regardless of whether it was applied as a coating on the surface or combined with the bulk, the photocatalytic influence seems to diminish after 4 months. One other disadvantage associated with the application of nanoparticles in the construction industry is that, when used to increase strength, these materials also have a larger density, which adds weight to the structure [239].

While nanomaterials (NMs) can enhance the qualities and performance of building materials, there are limitations on their use and commercialization, as well as issues with raw material availability and, as mentioned earlier, high production costs, which make some NMs difficult to obtain [240]. One of the biggest obstacles to using nanomaterials in the building industry is their expensive cost [241]. This is a result of the technology's novelty as well as the sophisticated machinery used in characterization and production procedures. However, costs have been demonstrated to decrease over time, and these costs may decrease much further as fabrication technologies progress. Currently, the higher cost of self-healing concrete compared to traditional OPC-based concretes is mostly caused by their superior attributes, limited knowledge about their application, and lower worldwide manufacturing. Despite their high cost, self-healing concretes based on nanomaterials should be evaluated for adoption due to their long-term benefits. Nanomaterials are anticipated to provide remarkable solutions for resolving any complex problems, leading to their use on a commercial scale and making them affordable [242].

Despite all of this, environmental issues and health risks are two main drawbacks of using nanoparticles in the building industry [243, 244]. Human health may be at risk from construction items with nanotechnology [245–247]. Given that constructive construction is found in a natural setting, all of the materials used in the facilities must, to the greatest extent possible, be environmentally friendly and compatible with the surrounding environment. The most common possible problems include nanoparticles entering groundwater, dispersing through dust into the atmosphere, and being exposed to potentially dangerous materials at the time of construction and during maintenance processes.

6.2 Future perspectives

The results of an extensive analysis of global nanotechnology advancements in construction, along with a survey of construction professionals, indicate that the aforementioned research areas will likely have a significant impact on the built environment and the construction industry in the upcoming 10 years. Notably, given the enormous amounts of materials involved, the most significant influence on the economy and the construction sector during this time is anticipated to come from improvements in production processes and advances in material performance attained through improved understanding and manipulation at the nanoscale [248]. Nanoclay has the potential to become a workable and sustainable solution for improving the performance and sustainability of building materials and practices by solving issues through creative research and development initiatives. In order to fully utilize nanoclay in the construction industry, more study and application are needed in the following areas:

- Refining nanoclay formulations to achieve even higher gains in strength, toughness, and durability

- Creating more environmentally friendly manufacturing processes for nanoclay

- Incorporating nanoclay into eco-friendly building materials that minimize resource consumption and reduce carbon emissions

- Involve the integration of nanoclay additives into 3D printing materials to create structures with enhanced strength, durability, and functionality

- Development of nanoclay additions for creative building materials with features like improved insulation, fire resistance, self-healing, or antibacterial qualities, opening up new opportunities

- Smart nanoclay additives are to be developed that can sense and react to changes in their environment, preventing structural failures and enhancing maintenance procedures

- Involves initiatives to create industry standards for the application of nanoclay in building materials and legal frameworks to handle environmental, health, and safety issues.

7. Conclusion

The utilization of nanoclays as fillers in the building and construction industries holds great potential for enhancing the performance of construction materials. The results from the literature review indicate that the incorporation of nanoclays can lead to improvements in mechanical properties, durability, fire resistance, and thermal insulation. Nanoclays offer unique characteristics, such as high aspect ratios and large specific surface areas, which contribute to enhanced load transfer, interfacial bonding, and barrier properties. However, there are challenges that need to be addressed, including dispersion and compatibility issues, cost considerations, and potential environmental impacts. Future trends in the field of nanoclays in construction include the development of multifunctional materials with additional properties, as well as exploring novel synthesis methods and surface modifications. Further research and development efforts are needed to optimize the manufacturing processes and ensure the sustainability of nanoclay-based materials. The application of nanoclays in the building and construction industries has the potential to revolutionize the field, leading to the development of sustainable, high-performance construction materials.

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