

PAPER • OPEN ACCESS

The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review

To cite this article: Aseel Mansi *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **961** 012085

View the [article online](#) for updates and enhancements.

You may also like

- [Effect of nano-clay fillers on mechanical and morphological properties of Napier/epoxy Composites](#)

K H Lim, M S A Majid, M J M Ridzuan et al.

- [Addition of nanometer clays to GFRPs for enhanced impact strength and fracture toughness](#)

Daksh Shelly, Karanbir Singh, Tarun Nanda et al.

- [Evaluation of mechanical behaviour of carbon fiber reinforced nanoclay filled IPN matrix composite](#)

G Suresh, S Vivek, L Ganesh Babu et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review

Aseel Mansi¹, Nadhim Hamah Sor^{2,3}, Nahla Hilal⁴, Shaker M A Qaidi⁵

¹Civil Engineering Department University of Technology, Baghdad, Iraq

² Civil Engineering Department, University of Garmian, Kalar, Kurdistan Region, Iraq

³ Department of Civil Engineering, Harran University, Sanliurfa, Turkey

⁴ University of Fallujah, Department of international Relation office, Iraq

⁵ Department of Civil Engineering, College of Engineering, University of Duhok, Duhok, Iraq

^{2,3} Corresponding author: nadhim.abdulwahid@garmian.edu.krd;
nadhim.hamahsor@gmail.com

Abstract. The use of nano clay to improve the qualities of construction materials and engineering applications has attracted a lot of discussion in recent years. This review article summarizes the influence of nano clay as a cement substitute and supplement on the performance of conventional and high-performance concrete. The addition of nano clay to high performance concrete revealed an increase in compressive and flexural strength, as well as durability attributes such as resistance to elevated temperatures and sulfate attack, while simultaneously decreasing porosity, permeability, and water absorption. This enhancement is a result of nano clay's roles as nano reinforcements, nanofillers, nucleation sites, and reactive pozzolans, which promote hydration and increase material characteristics.

Keywords: Nano clay; Self-compacting concrete; Workability; Hardened characteristics; Durability.

1. Introduction

Nanotechnology has emerged as a viable alternative for significantly increasing the strength and durability of construction materials over the last few decades. The phrase "nanotechnology" refers to the process of designing, fabricating, and utilizing functional structures with at least one characteristic dimension measured in nanometers. Due to the small size of its constituent particles or molecules, these materials and systems can be created to display innovative and physical, chemical, and biological characteristics have improved significantly. The explanation for this unique and extremely valuable behavior is that when structural features are between 10⁻⁹ m and 10⁻⁷ m (1 to 100 nm) in size, objects can exhibit physical properties that are markedly different from atoms or bulk materials. This can lead to new technical challenges and opportunities [1]. Clay minerals, which typically have a one-dimensional layer structure with a thickness of 0.7nm for 1:1 and 1nm for 2:1 ratio, exhibit a variety of surface shapes, including planar and interlayer. They are easily connected to internal and external surfaces and can be improved via ion exchange, adsorption, and grafting procedures. They



exhibit flexibility and harden upon drying and burning [2]. Nano clay particles are extensively manufactured mechanically using high-energy ball milling. They have a strong pozzolanic reactivity and a flaky, elongated, tiny, and platy particle form that can serve as a needle [3, 4].

Concrete is composed of two phases: a binding phase (cement matrix) and a particulate phase (aggregates). The particulate phase of ordinary strength concrete is much stronger than the binding phase. As a result, a concrete's mechanical qualities are strongly influenced by its cement matrix. By filling the cement paste nanopores with nano fine particles, the addition of nano fine particles can improve the characteristics of concrete through increased surface area and reactivity [5]. Due to the Architectural development of the construction industry, there is a high demand for large and complex structures, which often results in complicated concreting conditions. As a result, self-compacting concrete (SCC) has been developed as an alternative to traditional concrete. SCC is a term that refers to a concrete that compacts mostly through its own weight without vibrating. It's very fluid, so it can go around obstructions and fill all the nooks without the possibility of mortar or other concrete materials separating. There are no entrapped air or rock pockets. This form of concrete doesn't need to be compacted, saving time, labour, and energy [6]. However, there were many researchers used different types of binders in conventional and self-compacting concrete and mortar as cement replacement [7 – 15] or as base materials in geopolymer concrete and mortar production [16, 17].

SCC with nano clay has improved compressive, splitting, flexural strength, and durability properties like sulfate attack, fire and a higher density microstructure. On the other side, nano clay has decreased the workability, porosity, permeability, and water absorption. This improvement is due to nano clay particles work as nano fillers, nucleation sites, and reactive pozzolan in facilitating hydration and enhancing material properties [18]. On the other hand, Alani et al [19] concluded that the using of nano clay as cement replacement in SCC improved the mechanical characteristics and reduced the workability properties. Furthermore, Alobaidi et al. [20] reported that the using of nano fly ash in SCC mixtures had positive effect on hardened properties but their workability properties reduced. Moreover, Alrashedi et al. [21] concluded that strength of SCC developed by utilizing nano clay specially at later ages.

The purpose of this work is to provide an overview of nano clay's many features, the effect of nano clay on the properties of workability, hydration, strength, and durability performance of high-performance concrete.

2. Production Methods of Nanomaterial

Methods for manufacturing nano materials can usually be classified into top-down and bottom-up methods, as presented in Fig. 1. A top-down method is an easy method to fabricate sculpture from large marble block. Whereas, the bottom-up techniques function in the opposite direction: starting from the atomic or molecular precursors, the nano material, such as a nano-coating, is obtained and gradually assembled until the desired structure is formed [22]. The classification of top-down methods is shown in Table 1.

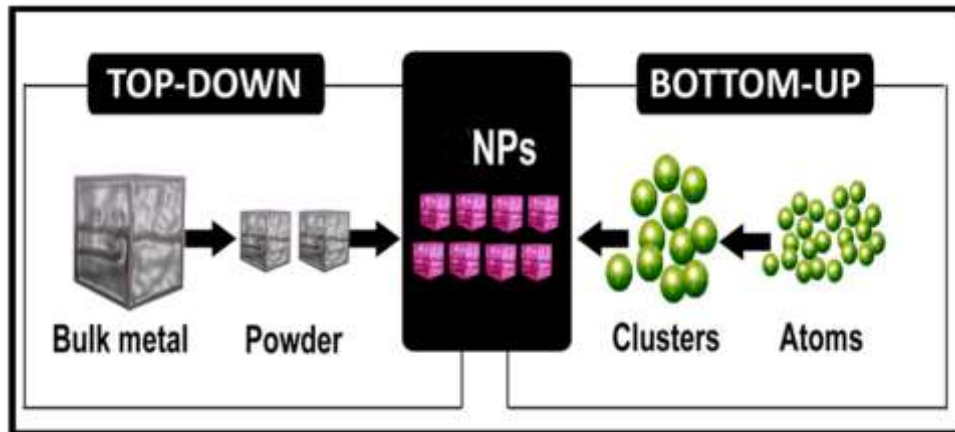


Figure 1: The "top-down" and "bottom-up" techniques are illustrated [23].

Table 1 the structure of top-down methods [24].

No	Top-down fabrication methods	Comments
1	Mechanical Energy	Mechanical methods employ a physical process that does not involve chemical change (a reaction).
2	Thermal Fabrication Methods	The thermal method employs a physical process (heating) that does not initiate chemical change (a reaction).
3	High Energy Fabrication Methods	The top-down production of nanomaterials is frequently accomplished using high-energy sources such as arcs, solar flux, and plasmas. These are not thermal procedures due to the fact that the source of heat is not traditional.
4	Chemical Fabrication Methods	The methods that use chemical transformation during a production process.
5	Lithographic Fabrication Methods	For numerous decades, lithography has been used to create printed circuit boards and computer boards.
6	Natural Fabrication Methods	Most of these natural processes are quite familiar, and there is no need to allocate any more time or space.

2.1. Mechanical Energy Methods

Mechanical energy methods are utilizing for ease, less expensive and less time-consuming fabrication of functional structural in bulk quantity. For such category, ball milling method is the simplest production method. Further, ball milling method uses kinetic energy of medium grinding to produces nanomaterials.

The other mechanical energy methods are compaction and consolidation in which nano materials are "put back together", and improved their properties. It is possible to make metallic alloys this way. Industry uses many top-down mechanical methods [25].

2.2. Ball Milling

Ball milling is a technique for producing ultrafine powders and nanostructured powders down to the submicron range, and it's widely employed across a wide range of industries. J. Benjamin invented the ball mill in 1966. The ability to create nano-crystalline powders and obtain huge quantities of

materials has been demonstrated over time to be an effective and easy technology [26]. Ball milling is a critical mechanical top-down process, a technique that uses mechanical attrition to manufacture nanoscale materials. Ball milling is a process in which the kinetic energy of a grinding medium (e.g., stainless steel ball bearings, zirconia, or porcelain) is immediately transmitted to coarse-grained metal, ceramic, or polymeric sample materials with the goal of reducing their size.

3. Types of Nano clays

Nano clay is nanoparticles, composed of layered mineral silicates, and according to their chemical compositions and morphologies, they are categorized into numerous categories such as bentonite, montmorillonite, kaolinite, halloysite, and hectorite. Table 2 and Figure 2 show the classification types of Nano clays and a schematic diagram of the structures. In this study, Nano clay is a kaolinite type. Kaolin or china clay is the name given to kaolinite-rich rocks [27].

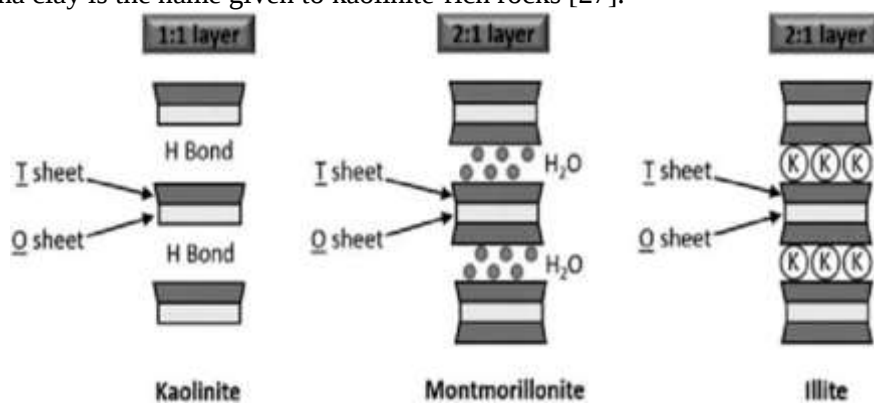


Figure 2: A schematic diagram of the Nano clays structure's [28].

It is a clay mineral that belongs to the industrial minerals group in which a layered silicate mineral along with one tetrahedral sheet is connected to octahedral sheet through oxygen atoms [29, 30].

Table 2: Classification types of Nano clays [31].

Family		Group	Formula
Phyllosilicates	TO (1:1)	Kaolinite	The reference plate is composed of a tetrahedral plate T and an octahedral plate O. The layer is approximately 0.7 nm thick. $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$ Kaolinite
	TOT (2:1)	Smectite, Talc, Mica, Montmorillonite, Sepiolite	There are two tetrahedral plates. T is produced on both sides of an octahedral plate O to form the reference plate. The layer has a thickness of roughly 1 nm. This group contains numerous minerals, several of which are essential components of clays.
	TOT : O (2:1:1)	Chlorite, Bentonite, Saponite	Three TOT plates and another isolated O plate comprise the reference plate. The layer is approximately 1,4 nm thick. $\text{Al}_2\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_8$ chlorite di-tri
Polysilicate	Natural	Kenyaite, Magadiite, Kanemite, Ilerite, Silhydrite, Zeolite	Magadiite ($\text{Na}_2\text{Si}_{14}\text{O}_{29} \cdot \text{H}_2\text{O}$)
	Synthetic	FluoroHectorite, Zeolite	
Double lamellar hydroxide	Synthetic	Hydrotalcite	Hydrotalcites: $(\text{Mg}_6\text{Al}_2(\text{OH})_{16})(\text{CO}_3^{2-})_4\text{H}_2\text{O}$

Where T: tetrahedral silicate sheet and O: octahedral aluminate sheet.

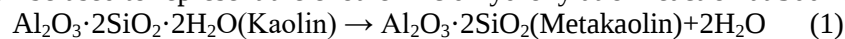
There are six-membered silicate rings in the kaolinite structure, which are linked to an octahedron of edge-sharing AlO_6 octahedral molecules that form four-member aluminate rings by shared oxygen atoms at the C-axis. The apical oxygens of the silicate and aluminate layers generate strong ion-covalent contacts that hold the other layers together, although the hydrogen bonds of the other layers are weaker [32].

It is found in the white mineral kaolinite, which is also known as dioctahedral phyllosilicate clay. It is composed of clay that is created as a result of the chemical weathering of aluminum silicate minerals such as feldspar [29, 33]. In mineralogy, the chemical formula for kaolinite is $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$.

4 .Properties of Nano clay

4.1. Physical Properties

Nano clay (NC) is derivative of kaolin ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), which changes from crystal to amorphous after treatment or endothermic dehydration [34]. Subsequent to dihydroxylation at temperatures between 600°C and 800°C , the large portion of octahedral alumina is changed into penta and more active tetra coordinated units [35]. Additionally, the high amorphous metakaolin (MK) and disordered phase variation are formed when the bonds between kaolinite layers are damaged, or the crystal structure is fully and/or partially damaged [36]. Finally, mechanical grinding is used to obtain NC. The equation (1) can be used to represent the exothermic dihydroxylation reaction at 500°C ~ 925°C [37]:



Metakaolin is a highly reactive pozzolan that has a similar reaction to silica fume. Compared to that silica fume, metakaolin has a refined microstructure which caused a better substantial strength and durability, permitting better water penetration resistance, and being cost-effective [38].

Table 3 illustrates that the surface area increases from 2 to 8 times when there is a change in clay size from micron to nanometer.

Table 3: Physical properties of Nano clay [39 – 43].

Specimen	Particle Size (nm)			Mean Size (nm)	Surface Area (m^2/g)	Percentage of Nano Particles (<500 nm)
	D10, Effective Size	D30	D60			
Clay	1612	5585	13325	1202	18.231	-
Nano clay	176	395	767	1114	48~170	40%

4.2. Chemical Properties

The chemical compositions of NC are presented in Table 4. NC has the highest content of SiO_2 (45.5 %to 89.6%), followed by Al_2O_3 (18.9 % to 42.3 %), both of which are important in improving cement hydration rate and setting time, while NC has a low content of CaO .

Table 4: Chemical compositions of Nano clay [39, 40, 43 – 46]

SiO_2	Al_2O_3	CaO	TiO_2	Fe_2O_3	K_2O	LOI
45.5~89.6	18.9~42.3	0.17~3.59	0.82~1.82	0.1~10.9	0.03~4.55	13~13.47

5. Hydration

According to some studies, NC enhanced the cement hydration reaction [47]. In the cement hydration process, Shoukry et al. [48] observed that as the NC replacement rate increased, CH content and X-ray diffraction peak intensity decreased marginally, while the C-S-H peak value increased. Moreover, about 6.7% reduction in CH content of NC cement paste has been observed as compared to CH content of ordinary cement paste [49]. However, beyond 10% replacement, there was no considerable variation in CH content of NC cement paste [50]. The reduction of 30.23J/g to 14.17J/g for CH enthalpy was observed when the NC replacement increased from 0% to 8%, and led the phase transition from good crystal to non-crystal. Moreover, the enthalpies of C-S-H, C_3ASH_6 and C_2ASH_8

were raised from 45.81 J/g, 0.85 J/g and 0.289 J/g to 46.91 J/g, 0.881 J/g, and 1.68 J/g respectively [41]. It was also noted a considerable enhancement in the crystalline structural forms [51].

The following points are the main aspects of the NC mechanism combination for accelerated cement hydration [52]:

1- The fine particles of NC induce nucleation, consume free CH, and generate needle-like secondary hydration products, significantly reducing the induction period's hydration.

2- When NC is added to cement particles, H_2SiO_4 is generated and combines with the available Ca^{2+} to make more C-S-H. These C-S-H molecules spread in the water between the cement particles and serve as seeds for the formation of denser C-S-H phases.

3- Unlike pure C3S, the production of the C-S-H phase does not occur exclusively on the particle surface, but also occurs in the pore region.

6. Workability

Aiswarya et al. [53] discovered that inducing more NC production Cement paste consistency could be improved by adding more water to the mixture. Cement paste's initial and final setting times have also been extended when the NC content was increased from 2% to 20%, and then dropped, reaching their maximum values at 6% and 4%, respectively. Similarly, in the Ultra-High-Performance Concrete (UHPC) test, a comparable result was observed [18]. In terms of fluidity, cementitious materials demonstrated a decreasing tendency when the nonlinear increase in NC content occurred. When 9% of NC was added to concrete, slump decreased by roughly 15.7 percent and workability of UHPC decreased from 178mm to 150mm [40], which was consistent with the results found by Senff et al [54]. Additionally, Alani et al. [19] and Alobaidi et al. [20] concluded that replacing cement with nano clay decreased the workability qualities of SCC.

This is largely due to the fact that the surface area of NC is so large, is easily formed into a flocculent network structure, has a low dispersability [55], and absorbs more free water during wetting [56]. This effect becomes more pronounced as the amount of NC in the solution increases. As a result, the range of NC content should be regulated to ensure adequate workability.

7. Mechanical Properties

7.1. Compressive Strength

It has been observed through numerous studies that the presence of NC caused an improvement in the compressive strength of the cementitious materials [55, 56]. Table 5 displays the impact of the addition of NC on compressive strengths of cementitious materials at 28 days.

Table 5. The effect of NC on compressive strength at 28 days.

Cementitious material	w/b ratio	Cont. of NC %	Compressive strength increment	Best content %	Ref.
Cement paste	0.27	4 - 5	8%→20%→-15%	10	[36]
	0.3	2 - 16	16%→54%→-10%		[59]
		2 - 14	16%→48%→-10%		[51]
	0.33~0.5	2 - 14	8.6%→59.4%→46.6%		[43]
	0.44	3 - 10	16%→24.6%→22%	6	[60]
	0.5~0.59	2 - 10	10%→63%→20%		[61]
Cement mortar	0.3	2 - 10	9.3%→22.6%→-1.3%	4	[62]
	0.4	5 - 10	28%→20%	5	[63]
		5	9.64%	-	[42]
	0.485	3	54%	-	[64]
	0.5	2.5 - 10	15%→34%→19%	7.5	[65]
		6	18%	-	[66]

	0.54	2 - 8	1.2%→7%	8	[41]
		3	7.76%	-	[46]
		2 - 14	8.8%→42%→20%	10	[45]
		2 - 10	20%→57%		[48]
	0.6	5 - 15	23%→8%	5	[67]
Normal concrete	0.48	2 - 5	5.27%→15.45%	5	[68]
	0.5	10	26.32%	-	[69]
	0.53	3 - 10	42.2%→ 63.1%	10	[6]
Ultra high performance concrete (UHPC)	0.2	1 - 9	12%→ -16.5	1	[18]
		1 - 10	8.5%→-8.5%		[40]
SCC	0.34	1 - 3	2.3% →10.8%	3	[70]
	0.44	2 - 8	3.2% →15.8%	8	[21]

From the previous Table which illustrated that the inclusion of NC in cementitious materials has a significant effect on compressive strengths, and resulted in substantial increase in it a certain percentage of NC addition [43].

However, a possible reduction in compressive strength can occur when the quantity of NC exceeds the best value. Excess NC tends to aggregate and adsorb around cement particles, slowing down cement hydration reaction and decreasing the C3S and C2S matrix phases, which are both caused by agglomeration [63].

Additionally, the excess quantity of NC causes a weak interfacial transition zone (ITZ) in the matrix [71], and its dispersion defect causes to produce fewer points of contact with the matrix and produce a negative effect on bonding with cement particles [72, 73].

Although the other mixing information such as chemical and mineral admixtures, curing conditions, and w/b ratio are almost similar, but the best contents of NC has a significant effect on compressive strengths. As a result, more studies should be conducted and discussed better to apprehend the various effects of NC on compressive strengths [74].

7.2. Flexural and Splitting Tensile Strength

Table 6 illustrate that the addition of NC can significantly increase the flexural and splitting tensile strengths of cementitious materials.

Table 6: Flexural strengths and splitting tensile strength of cementitious materials with NC at 28 days

Cementitious material	w/b ratio	Cont. of NC %	Flexural strength increment %	Splitting tensile strength increment %	Best content %	Ref.
Cement paste	0.3	2 -14	14→36→-25	-	10	[51]
	0.33-0.5	2 -14	3.9→58→38	-		[43]
Cement mortar	0.5	2.5-10	6.4→29→19	-	7.5	[65]
		2 - 8	-	10→49	8	[41]
	0.54	2 - 4	12.6→52→21	-	10	[45]
		2 - 10	20→59	-		[48]
	0.6	5 - 15	8→4	-	5	[67]
Normal concrete	0.5	10	-	25.87	-	[69]
	0.53	3 - 10	-	0→46.8	10	[6]
SCC	0.34	1 - 3	-	4.6 →18.5	3	[70]
	0.44	2 - 8	7 →10.5	5 →10	8	[21]

7.3 Mechanism of NC to Increase Strength

7.3.1. The impact of filling.

Nanometer-sized of NC has a substantial impact on the filling capacity of cement ingredients. Although the NC particles are 1000 times smaller than the size of cement particles (micrometer), but still NC could fill the microstructure gaps, voids and could diminish the ITZ defects [75, 76].

The SEM image as shown in Figure 3 shows that the incorporation of NC fills the voids and pores and resulting a more compact structure, also opposed to the weak microstructure of control mortar [48], which corresponds with the other studies [46, 66].

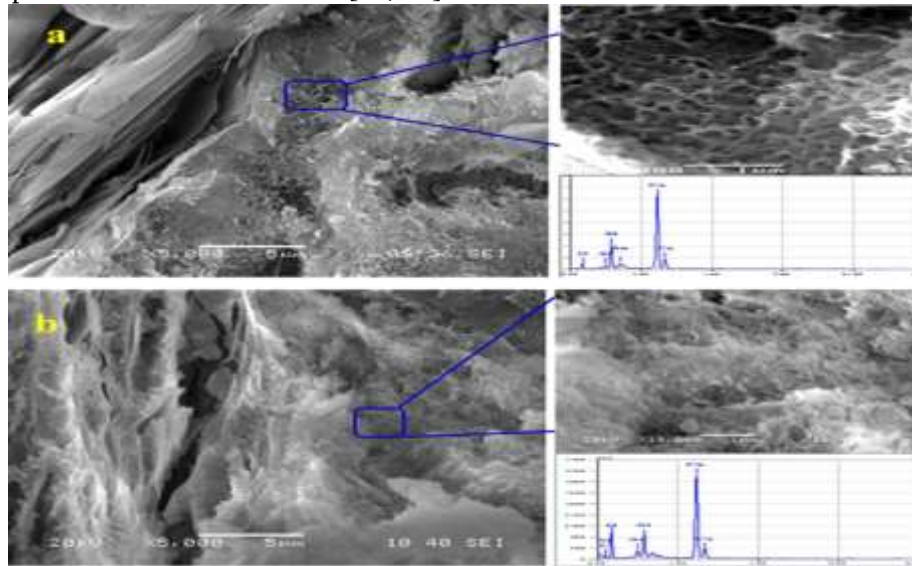


Figure 3: SEM images and EDX patterns of cement mortar (a) 0% NC and (b) 10% NC [48].

7.3.2. The effect of nucleation.

Figure 4 depicts that the NC helps clinker hydration by the available surface area to sedimentation hydrates from the interstitial solution [77].

The high surface energy of NC provides the thermodynamic drive for this process. Rather than critical nucleation, NC behaves as a source to initiate precipitation [41], and the hydrate phases start as the ionic concentration reaches saturation. Meanwhile, NC enables continuous growth of the C-S-H phase, prefabricate nucleus for the hydration process, aggregation of C-S-H in the network structure. It could also promote hydration reaction of cement [72], and develop uniform and dense microstructure [78]. The nucleus of a crystal is beneficial for increasing the early strength of cement, but the nucleation effect is lost when the cement reaction completes [47].

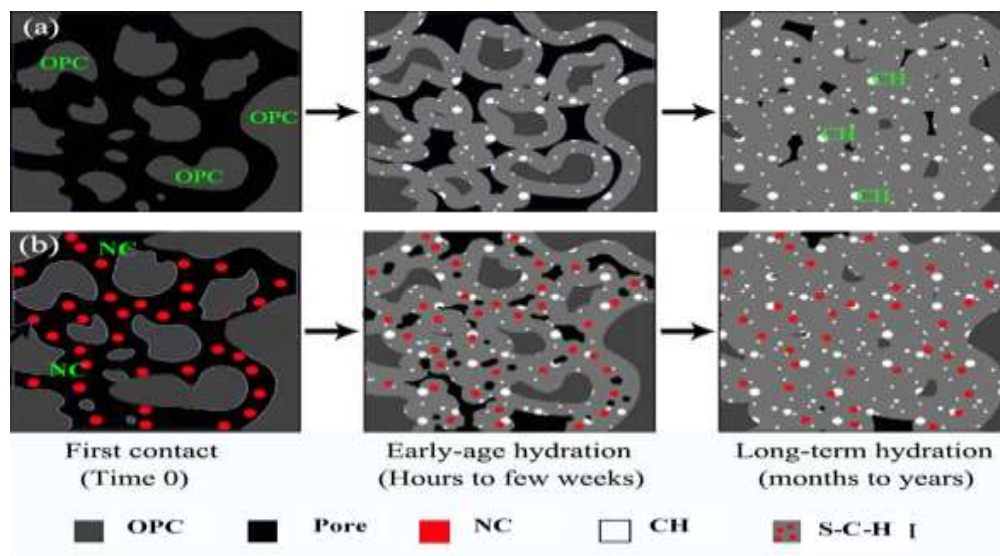


Figure 4. The hydration model of (a) Ordinary Portland cement and (b) Concrete with NC [77].

7.3.3. The influence of bridging.

The inclusion of NC particles works as a fiber between cement products, creates bridge between matrix and reinforcement, and provides resistance to cracks and crack propagation as shown in SEM images Figure 5 [41, 51, 66, 67].

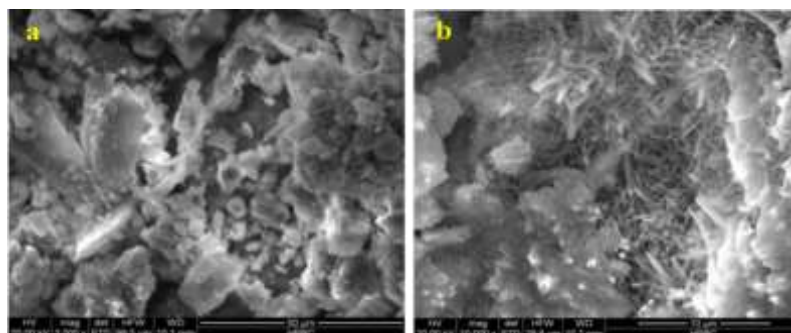


Figure 5: SEM images of mortar at 28 days (a) 0% NC; (b) 8% NC [41].

8. Durability

8.1 Water Absorption

Table 7 summarises the effect of NC on the coefficient of capillary water absorption of the cementitious materials. In general, as the NC content increases, the water absorption coefficient decreases [79]. Also, the geometry and size of the pore system should be directly linked to the mechanism of capillary water absorption [80]. The improved pore structure can be attributed mostly to the additional C-S-H gel produced by NC's pozzolanic reaction and to its own microaggregate impact, which fills the micropores between cement particles [48, 49, 81] and reduces the water absorption of cement paste [45].

Table 7. Coefficients of capillary absorption of cementitious compositions containing NC.

Cementitious material	Cont. of NC %	Capillary absorption coefficient		Reduced by (%)	Ref.
		Control sample	Sample with NC		
Cement paste	2 - 14	0.55 (kg/m ²) / min ^{-1/2}	0.22, 0.41 (kg/m ²) / min ^{-1/2}	25.4 - 60	[43]

	6	$0.266 \text{ (kg/m}^2\text{) / s}^{-1/2}$	$0.154 \text{ (kg/m}^2\text{) / s}^{-1/2}$	42	[61]
Cement mortar	2 - 14	$0.33 \text{ (kg/m}^2\text{) / min}^{-1/2}$	$0.12, 0.22 \text{ (kg/m}^2\text{) / min}^{-1/2}$	33 - 63.6	[45]
	5 - 10	-	-	38.02 - 51.34	[63]
	2 - 10	$0.056 \text{ (kg/m}^2\text{) / min}^{-1/2}$	$0.014, 0.04 \text{ (kg/m}^2\text{) / min}^{-1/2}$	28.5 - 75	[48]
Normal concrete	3 - 10	-	-	16.6 - 25.6	[6]

8.2. Elevated temperature resistance

Morsy et al. [67] studied the influence of adding different NC by weight percentages (5%–15%) on the compressive and flexural strength of cement mortar at various elevated temperatures. The compressive and flexural strengths were gradually improved with increasing temperature up to 250°C, and beyond this temperature, both strengths decreased until the temperature reached 800°C. At 250°C, compressive and flexural strength increased by 5.2%~36.6% and 3.4%~27%, respectively, while compressive strength decreased by 46.5%~61.5% at 800°C for mixes of (5,10 and 15) % NC.

Based on similar experiments, the compressive strength and thermal conductivity coefficients of SCC at 25 – 1000°C for one hour with NC concentrations varied from 0.1% to 0.5% were studied by Wang [82]. The results illustrated that when the temperature was below 300 °C, NC concrete increased strength; when the temperature was between 440 and 580 °C, strength was significantly reduced; and when the temperature exceeded 1000 °C, the strength was less than 10% of its original strength.

The excess hydration of unhydrated cement particles results steam effect due to internal autoclaving, and the pozzolanic reaction of NC resulted extra C-S-H gel with smaller Ca/Si ratio. The additional hydration products help to bridge the pore system, reduce the thermal stresses around the pores. Moreover, the calcium aluminates hydrate (C-A-H) phases can increase the compressive strength of blended cement mortars up to 200°C~250°C [83].

Furthermore, the incorporation of NC in cementitious products would be made the cement matrix had greater inclusions of gel-like hydration products which could make it more fire resistant. However, the excess hydration can cause a loss in strength of the cementitious products. It is mainly due to that CH decomposes into CaO and H₂O at 500°C, and CaCO₃ decomposes with the effusion above 600°C, and caused a reduction in free water, and decreased strength and elasticity modulus [84]. Furthermore, the temperature gradient causes high thermal tension, which leads to an increase in micro cracks and a weakening of structure's compactness [85].

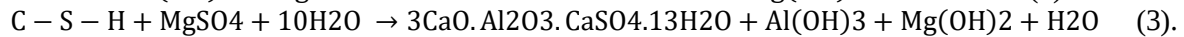
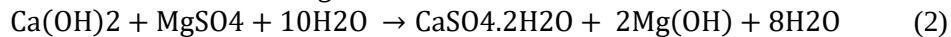
8.3. Resistance to Sulfate Attack

The porosity and pore size distribution of concrete significantly impacts its durability. Moreover, such factors influenced the transport properties of the main harmful agents such as gases, water, and ions. These transport properties can be deteriorated concrete by physical and/or chemical attack [86]. The presence of sulfate ions in seawater, groundwater, and soil can decline reinforced concrete structures by means of expansion, spalling, cracking, swelling of concrete elements. These characteristics can be caused by a variety of factors such as the type of cement, type of sulfate cation, sulfate concentration, and exposure period. Many sulfate-damaged structures need rehabilitation or, in the most violent cases, reconstruction [87].

Sulfate ions can react with sources of alumina (hydration products such as mono sulfa aluminate (AFm) and unhydrated tricalcium aluminate (C₃A)) to produce ettringite. Also, the produces gypsum with the help of calcium (calcium hydroxide (CH)) or C-S-H gel). However, such production resulting in loss of substantial strength and crack initiation and propagation. It is mainly because of the driving force of crystallisation pressure impacts on the pore walls, and such driving force results crystal growth of gypsum and ettringite [88]. Tian and Cohen [89], obtained (3–4) MPa tensile strength for cement-based materials, and concluded that the tensile stress caused by gypsum formation had a significant part for the crack initiation and expansion. Müllauer et al, [90] concluded that the

formation of ettringite in tiny pores (10–50 nm) resulted tensile stress of 8 MPa, and caused crack expansion which led to failure of the cementitious structure.

If the attack solution is magnesium sulfate (MgSO_4), all cement minerals, including C-S-H, are targeted. The stability of the C-S-H gel is decreased as a result of the development of the relatively insoluble and low-alkaline brucite ($\text{Mg}(\text{OH})_2$) in interaction with dissolved CH. Additionally, MgSO_4 reacts immediately with calcium silicate hydrate, transforming it into gypsum and a weak magnesium silicate hydrate (M-S-H). Due to the presence of a thick brucite coating on the surface, surface damage is unnoticeable until late in the attack, whereas strength loss begins early [91]. Equations (2) and (3) can illustrate the mechanics of the magnesium sulfate attack



Many researchers have shown in recent years that using nanomaterials may greatly increase the sulfate resistance of cement-based materials, with this effect becoming more noticeable at earlier ages [92, 93].

The great pozzolanic reactivity that caused the reduction of CH, as well as hardened cement-based materials were studied for its influence on the microstructure [94]. Cement mortar and concrete's susceptibility to sulfate attack has only been studied by a handful of scientists. The microstructure of cement mortar is strengthened by the addition of nano clay as a filler. It also serves as a mortar activator, encouraging the pozzolanic reaction.

Hakamy et al. [95] investigated the effects of Nano clay on cement composite properties. They reported a decrease in porosity and water absorption in cement nanocomposites containing 1 wt.% Nano clay. They also discovered that cement nanocomposites had higher in density, strength, fracture toughness, and hardness than the control mix.

Hosseini et al. [96] studied the effects of adding 0.25, 0.50, 0.75, and 1% Nano clay to SCC mix. The water penetration depth was lowered by 17, 27, 39, and 43 percent, respectively. Water penetration into the SCC mix is reduced, making it more resistant to sulfate attacks.

9. Conclusions

Previous research has demonstrated that using nano clay as a cement substitute and addition in concrete has the potential to increase the strength, microstructure, hydration and durability performance of conventional and high performance concrete. nano clay is a hydrophilic material that swells and absorbs water when used in cement, this behavior can be minimized by altering the nano clay structure. All the qualities of nano clay, such as catalyst, nano fillers, highly reactive pozzolanas and nano reinforcements, counterbalance and nucleation sites influence the performance of high performance concrete. Concrete's mechanical characteristics and microstructure performance can be enhanced by nano clay, however the concrete's water permeability can be decreased as a result of this enhancement. Accordingly, the use of nano clay in the high performance concrete has a potential in order to develop the strength property which is also enhance the durability performance such as permeability, chemical resistance and water absorption of concrete. On the other hand, nano clay improve the cohesion and homogeneous of microstructure of concrete. However, the segregation and bleeding characteristics of concrete reduced by nano clay incorporation in the concrete mixtures.

References

- [1] R. W. Kelsall, I. W. Hamley, and M. Geoghegan, *Nanoscale science and technology*. Wiley Online Library, 2005.
- [2] A. El Mir and S. G. Nehme, "Utilization of industrial waste perlite powder in self-compacting concrete," *J. Clean. Prod.*, vol. 156, pp. 507–517, 2017.
- [3] W.-J. Long, Y. Gu, J. Liao, and F. Xing, "Sustainable design and ecological evaluation of low binder self-compacting concrete," *J. Clean. Prod.*, vol. 167, pp. 317–325, 2017.
- [4] H. H. Alghazali, "Behavior and temporal-based effects of sustainable self-consolidating concrete in bridge structures," 2018.

- [5] S. A. Shakrani, A. Ayob, and M. A. A. Rahim, "A review of nanoclay applications in the pervious concrete pavement," in *AIP Conference Proceedings*, 2017, vol. 1885, no. 1, p. 20049.
- [6] A. M. Ibrahim, "The effect of nano metakaolin material on some properties of concrete," *Diyala J. Eng. Sci.*, vol. 6, no. 1, pp. 50–61, 2013.
- [7] Aadi, A.S., Sor, N.H. and Mohammed, A.A., 2021, August. The behavior of eco-friendly self-compacting concrete partially utilized ultra-fine eggshell powder waste. In *Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012143). IOP Publishing.
- [8] Bheel, Naraindas, Montasir Osman Ahmed Ali, Yue Liu, T. Tafsirojjaman, Paul Awoyera, Nadhim Hamah Sor, and Lenin Miguel Bendezu Romero. "Utilization of Corn Cob Ash as Fine Aggregate and Ground Granulated Blast Furnace Slag as Cementitious Material in Concrete." *Buildings* 11, no. 9 (2021): 422.
- [9] Hilal, Nahla, Nadhim Hamah Sor, and Rabar H. Faraj. "Development of eco-efficient lightweight self-compacting concrete with high volume of recycled EPS waste materials." *Environmental Science and Pollution Research* (2021): 1-24. <https://doi.org/10.1007/s11356-021-14213-w>.
- [10] Öz HÖ, Gesoglu M, Güneyisi E, Sor NH (2017) Self-consolidating concretes made with cold-bonded fly ash lightweight aggregates. *ACI Mater J* 114(3). <https://doi.org/10.14359/51689606>
- [11] Abed, J.M., Khaleel, B.A., Aldabagh, I.S. and Sor, N.H., 2021, August. The effect of recycled plastic waste polyethylene terephthalate (PET) on characteristics of cement mortar. In *Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012121). IOP Publishing.
- [12] Mohammed, A.S., Hilal, N.N., Ali, T.K.M. and Sor, N.H., 2021, August. An investigation of the effect of walnut shell as sand replacement on the performance of cement mortar subjected to elevated temperatures. In *Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012034). IOP Publishing.
- [13] Sor NAH (2018) The effect of superplasticizer dosage on fresh properties of self-compacting lightweight concrete produced with coarse pumice aggregate. *J Garmian Univ* 5(2):190–209
- [14] Hamah Sor, Nadhim, Nahla Hilal, Rabar H. Faraj, Hemn Unis Ahmed, and Aryan Far H. Sherwani. "Experimental and empirical evaluation of strength for sustainable lightweight self-compacting concrete by recycling high volume of industrial waste materials." *European Journal of Environmental and Civil Engineering* (2021): 1-18. <https://doi.org/10.1080/19648189.2021.1997827>.
- [15] Ahmed, Hemn Unis, Azad A. Mohammed, Serwan Rafiq, Ahmed Salih Mohammed, Amir Mosavi, Nadhim Hamah Sor, and Shaker M.A. Qaidi. "Compressive Strength of Sustainable Geopolymer Concrete Composites: A state-of-the-Art Review." *Sustainability* 11, (2021).
- [16] Bheel, Naraindas, Paul Awoyera, T. Tafsirojjaman, and Nadhim Hamah Sor. "Synergic effect of metakaolin and groundnut shell ash on the behavior of fly ash-based self-compacting geopolymer concrete." *Construction and Building Materials* 311 (2021): 125327.
- [17] Mermerdaş K, Süleyman İPEK, Sor NH, Mulapeer ES, Ekmen Ş (2020) The impact of artificial lightweight aggregate on the engineering features of geopolymer mortar. *Türk Doğa ve Fen Dergisi* 9(1): 79–90. <https://doi.org/10.46810/tdfd.718895>.
- [18] A. M. Fadzil, M. S. M. Norhasri, M. S. Hamidah, M. R. Zaidi, and J. M. Faizal, "Alteration of nano metakaolin for ultra high performance concrete," in *InCIEC 2013*, Springer, 2014, pp. 887–894.
- [19] Alani, Nibras Y., Ibrahim A. Al-Jumaily, and Nahla Hilal. "Effect of nanoclay and burnt limestone powder on fresh and hardened properties of self-compacting concrete." *Nanotechnology for Environmental Engineering* 6, no. 1 (2021): 1-26.
- [20] Alobaidi, Yusra M., Nahla N. Hilal, and Rabar H. Faraj. "An experimental investigation on the nano-fly ash preparation and its effects on the performance of self-compacting concrete at normal and elevated temperatures." *Nanotechnology for Environmental Engineering* 6, no. 1 (2021): 1-13.
- [21] Alrashedi, Baydaa, and Maan Hassan. "Effects of nano and micro size of clay particles on the compressive and tensile strength properties of self-consolidating concrete." In *MATEC Web of Conferences*, vol. 162, p. 02030. EDP Sciences, 2018.
- [22] L. Fiiipponi and D. Sutherland, *Nanotechnologies: principles, applications, implications and hands-on activities: A compendium for educators*. European Union, Directorate General for Research and Innovation, 2012.

- [23] B. Domènech, J. Bastos-Arrieta, A. Alonso, J. Macanás, M. Muñoz, and D. N. Muraviev, "Bifunctional polymer-metal nanocomposite ion exchange materials," *Ion Exch. Technol.*, pp. 35–72, 2012.
- [24] G. L. Hornyak, J. Dutta, H. F. Tibbals, and A. Rao, *Introduction to nanoscience*. CRC press, 2008.
- [25] K. K. Chattopadhyay, *Introduction To Nanoscience And Nanotechnology*. PHI Learning Pvt. Ltd., 2009.
- [26] Z. Rizlan and O. Mamat, "Process parameters optimization of silica sand nanoparticles production using low speed ball milling method," *Chinese J. Eng.*, vol. 2014, 2014.
- [27] B. B. Sabir, S. Wild, and J. Bai, "Metakaolin and calcined clays as pozzolans for concrete: a review," *Cem. Concr. Compos.*, vol. 23, no. 6, pp. 441–454, 2001.
- [28] M. Zhang, "The effect of clay minerals on copper and gold flotation," 2016.
- [29] Z. Adamis, R. B. Williams, and J. Fodor, *Bentonite, kaolin, and selected clay minerals*, no. 231. World health organization, 2005.
- [30] B. N. Rolfe, R. F. Miller, and I. S. McQueen, "Dispersion characteristics of montmorillonite, kaolinite, and illite clays in waters of varying quality, and their control with phosphate dispersants," 1960.
- [31] H. Z. Harraz, "Nano clay and it's applications By :," no. April 2016, 2017.
- [32] S. Sperinck, P. Raiteri, N. Marks, and K. Wright, "Dehydroxylation of kaolinite to metakaolin—a molecular dynamics study," *J. Mater. Chem.*, vol. 21, no. 7, pp. 2118–2125, 2011.
- [33] A. Chakchouk, L. Trifi, B. Samet, and S. Bouaziz, "Formulation of blended cement: Effect of process variables on clay pozzolanic activity," *Constr. Build. Mater.*, vol. 23, no. 3, 2009.
- [34] P. Blanchart, S. Deniel, and N. Tessier-Doyen, "Clay structural transformations during firing," in *Advances in Science and Technology*, 2010, vol. 68, pp. 31–37.
- [35] C. Belver and M. Á. Vicente, "Porous silica gel by acid leaching of metakaolin," in *Materials Syntheses*, Springer, 2008, pp. 47–51.
- [36] S. M. A. El-Gamal, M. S. Amin, and M. Ramadan, "Hydration characteristics and compressive strength of hardened cement pastes containing nano-metakaolin," *HBRC J.*, vol. 13, no. 1, 2017.
- [37] A. M. Rashad, "Metakaolin as cementitious material: History, scours, production and composition—A comprehensive overview," *Constr. Build. Mater.*, vol. 41, pp. 303–318, 2013.
- [38] E. Ghafari, H. Costa, and E. Júlio, "Critical review on eco-efficient ultra high performance concrete enhanced with nano-materials," *Constr. Build. Mater.*, vol. 101, pp. 201–208, 2015.
- [39] M. A. Fadzil, M. S. M. Nurhasri, M. A. Norliyat, M. S. Hamidah, M. H. W. Ibrahim, and R. Z. Assrul, "Characterization of Kaolin as Nano Material for High Quality Construction," in *MATEC Web of Conferences*, 2017, vol. 103, p. 9019.
- [40] M. S. M. Nurhasri, M. S. Hamidah, and A. M. Fadzil, "Inclusion of nano metaclayed as additive in ultra high performance concrete (UHPC)," *Constr. Build. Mater.*, vol. 201, pp. 590–598, 2019.
- [41] M. S. Morsy, H. Shoukry, M. M. Mokhtar, A. M. Ali, and S. A. El-Khodary, "Facile production of nano-scale metakaolin: An investigation into its effect on compressive strength, pore structure and microstructural characteristics of mortar," *Constr. Build. Mater.*, vol. 172, pp. 243–250, 2018.
- [42] R. Gopalakrishnan, "Mechanical and microstructure studies on nano-clay admixed cement mortar," *Rasayan J. Chem.*, vol. 9, pp. 331–334, 2016.
- [43] H. Shoukry, "Development of Nano Modified Eco-Friendly Green Binders for Sustainable Construction Applications," *Nano Hybrids Compos.*, vol. 24, pp. 25–36, 2019.
- [44] S. M. A. El-Gamal, F. S. Hashem, and M. S. Amin, "Influence of carbon nanotubes, nanosilica and nanometakaolin on some morphological-mechanical properties of oil well cement pastes subjected to elevated water curing temperature and regular room air curing temperature," *Constr. Build. Mater.*, vol. 146, pp. 531–546, 2017.
- [45] K. Al-Jabri and H. Shoukry, "Influence of nano metakaolin on thermo-physical, mechanical and microstructural properties of high-volume ferrochrome slag mortar," *Constr. Build. Mater.*, vol. 177, pp. 210–221, 2018.

- [46] G. Xiaoyu, F. Yingfang, and L. Haiyang, "The compressive behavior of cement mortar with the addition of nano metakaolin," *Nanomater. Nanotechnol.*, vol. 8, p. 1847980418755599, 2018.
- [47] X. F. Li and H. Q. Chen, "The influence of nano-kaolin to cement performance," in *Applied Mechanics and Materials*, 2012, vol. 174, pp. 1208–1213.
- [48] H. Shoukry, M. F. Kotkata, S. A. Abo-EL-Enein, M. S. Morsy, and S. S. Shebl, "Enhanced physical, mechanical and microstructural properties of lightweight vermiculite cement composites modified with nano metakaolin," *Constr. Build. Mater.*, vol. 112, pp. 276–283, 2016.
- [49] H. Shoukry, M. F. Kotkata, S. A. Abo-el-Enein, and M. S. Morsy, "Flexural strength and physical properties of fiber reinforced nano metakaolin cementitious surface compound," *Constr. Build. Mater.*, vol. 43, pp. 453–460, 2013.
- [50] S. M. A. El-Gamal, F. S. Hashem, and M. S. Amin, "Thermal resistance of hardened cement pastes containing vermiculite and expanded vermiculite," *J. Therm. Anal. Calorim.*, vol. 109, no. 1, pp. 217–226, 2012.
- [51] A. E. Al-Salami, M. S. Morsy, S. Taha, and H. Shoukry, "Physico-mechanical characteristics of blended white cement pastes containing thermally activated ultrafine nano clays," *Constr. Build. Mater.*, vol. 47, pp. 138–145, 2013.
- [52] P. min Zhan *et al.*, "Utilization of nano-metakaolin in concrete: A review," *J. Build. Eng.*, vol. 30, p. 101259, 2020.
- [53] S. Aiswarya, A. G. Prince, and A. Narendran, "Experimental investigation on concrete containing nano-metakaolin," *IRACST. Eng. Sci. Technol.*, vol. 3, no. 1, pp. 180–187, 2013.
- [54] L. Senff, J. A. Labrincha, V. M. Ferreira, D. Hotza, and W. L. Repette, "Effect of nano-silica on rheology and fresh properties of cement pastes and mortars," *Constr. Build. Mater.*, vol. 23, 2009.
- [55] M. Amin and K. Abu el-Hassan, "Effect of using different types of nano materials on mechanical properties of high strength concrete," *Constr. Build. Mater.*, vol. 80, pp. 116–124, 2015.
- [56] Y. Knop and A. Peled, "Setting behavior of blended cement with limestone: influence of particle size and content," *Mater. Struct.*, vol. 49, no. 1–2, pp. 439–452, 2016.
- [57] M. S. M. Norhasri, M. S. Hamidah, and A. M. Fadzil, "Applications of using nano material in concrete: A review," *Constr. Build. Mater.*, vol. 133, pp. 91–97, 2017.
- [58] M. Heikal and N. S. Ibrahim, "Hydration, microstructure and phase composition of composite cements containing nano-clay," *Constr. Build. Mater.*, vol. 112, pp. 19–27, 2016.
- [59] S. A. Abo-El-Enein, M. S. Amin, F. I. El-Hosiny, S. Hanafi, T. M. ElSokkary, and M. M. Hazem, "Pozzolan activity and hydraulic activity of nano-metakaolin," *HBRC J.*, vol. 10, no. 1, pp. 64–72, 2014.
- [60] A. D. Salman, "Studying The Effect of Nano-Metakaolin Admixture Material On Mechanical Properties of Oil Well Cement (OWC)," *Eng. Technol. J.*, vol. 35, no. 9 Part A, 2017.
- [61] K. Al-Jabri, H. Shoukry, and A. Abdel Aal, "Physico-mechanical properties of lime-silica fume pastes modified with nano-metakaolin," *Proc. Inst. Civ. Eng. Build.*, vol. 173, no. 9, 2020.
- [62] M. Kaur, J. Singh, and M. Kaur, "Microstructure and strength development of fly ash-based geopolymer mortar: Role of nano-metakaolin," *Constr. Build. Mater.*, vol. 190, pp. 672–679, 2018.
- [63] M. F. Ghazy, M. A. A. Elaty, and R. S. Elkhori, "Performance of blended cement mortars incorporating nano-metakaolin particles at elevated temperatures," in *Proceeding of the International Conference on Advances in Structural and Geotechnical Engineering, Hurgada, Egypt*, 2015.
- [64] M. Heikal and N. S. Ibrahim, "Hydration, microstructure and phase composition of composite cements containing nano-clay," *Constr. Build. Mater.*, vol. 112, pp. 19–27, 2016.
- [65] M. S. Morsy, Y. Al-Salloum, T. Almusallam, and H. Abbas, "Effect of nano-metakaolin addition on the hydration characteristics of fly ash blended cement mortar," *J. Therm. Anal. Calorim.*, vol. 116, no. 2, pp. 845–852, 2014.
- [66] M. S. Morsy, S. H. Alsayed, and M. Aqel, "Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar," *Constr. Build. Mater.*, vol. 25, no. 1, 2011.
- [67] M. S. Morsy, Y. A. Al-Salloum, H. Abbas, and S. H. Alsayed, "Behavior of blended cement mortars containing nano-metakaolin at elevated temperatures," *Constr. Build. Mater.*, vol. 35, 2012.

- [68] G. M. Habeeb, J. M. Al-Jeabory, and M. H. Majeed, "Sustainable performance of reactive powder concrete by using nano meta kaolin," *J. Eng. Sustain. Dev.*, vol. 22, no. 02 Part-6, pp. 96–106, 2019.
- [69] Z. H. A. Alsallami, "Effect of sulfate in sand on some mechanical properties of nano metakaolin normal concrete," *J. Babylon Univ. Sci.*, vol. 24, no. 2, p. 1, 2016.
- [70] M. A. Mirgozar Langaroudi and Y. Mohammadi, "Effect of nano-clay on workability, mechanical, and durability properties of self-consolidating concrete containing mineral admixtures," *Constr. Build. Mater.*, vol. 191, pp. 619–634, 2018.
- [71] K.-Y. Liao, P.-K. Chang, Y.-N. Peng, and C.-C. Yang, "A study on characteristics of interfacial transition zone in concrete," *Cem. Concr. Res.*, vol. 34, no. 6, pp. 977–989, 2004.
- [72] H. A. Abdel Gawwad, S. Abd El-Aleem, and A. S. Faried, "Influence of nano-silica and-metakaolin on the hydration characteristics and microstructure of air-cooled slag-blended cement mortar," *Geosystem Eng.*, vol. 20, no. 5, pp. 276–285, 2017.
- [73] A. Nadeem, S. A. Memon, and T. Y. Lo, "The performance of fly ash and metakaolin concrete at elevated temperatures," *Constr. Build. Mater.*, vol. 62, pp. 67–76, 2014.
- [74] A. M. Diab, M. Abd Elmoaty, and A. A. Aly, "Long term study of mechanical properties, durability and environmental impact of limestone cement concrete," *Alexandria Eng. J.*, vol. 55, no. 2, pp. 1465–1482, 2016.
- [75] A. M. El Nagar and H. M. Khater, "Development of High Thermal Stability Geopolymer Composites Enhanced by Nano Metakaolin," *J. Build. Mater. Struct.*, vol. 6, no. 1, pp. 10–19, 2019.
- [76] M. S. Morsy and H. A. Aglan, "Development and characterization of nanostructured-perlite-cementitious surface compounds," *J. Mater. Sci.*, vol. 42, no. 24, pp. 10188–10195, 2007.
- [77] Y. Reches, "Nanoparticles as concrete additives: Review and perspectives," *Constr. Build. Mater.*, vol. 175, pp. 483–495, 2018.
- [78] R. Siddique and J. Klaus, "Influence of metakaolin on the properties of mortar and concrete: A review," *Appl. Clay Sci.*, vol. 43, no. 3–4, pp. 392–400, 2009.
- [79] A. M. Diab, H. E. Elyamany, M. Abd Elmoaty, and M. M. Sreh, "Effect of nanomaterials additives on performance of concrete resistance against magnesium sulfate and acids," *Constr. Build. Mater.*, vol. 210, pp. 210–231, 2019.
- [80] M. Zhang and H. Li, "Pore structure and chloride permeability of concrete containing nano-particles for pavement," *Constr. Build. Mater.*, vol. 25, no. 2, pp. 608–616, 2011.
- [81] I. Z. Saa'id, A. H. Osama, and F. E. Omar, "Compration between the effect of addition of nano-calcium carbonate and nano-kaoline on developing the properties of reinforced," *Intellekt. Sist. Proizv.*, vol. 16, no. 3, pp. 147–159, 2018.
- [82] W. C. Wang, "Compressive strength and thermal conductivity of concrete with nanoclay under Various High-Temperatures," *Constr. Build. Mater.*, vol. 147, pp. 305–311, 2017.
- [83] S.-H. Han and J.-K. Kim, "Effect of temperature and age on the relationship between dynamic and static elastic modulus of concrete," *Cem. Concr. Res.*, vol. 34, no. 7, pp. 1219–1227, 2004.
- [84] K. Sakr and E. El-Hakim, "Effect of high temperature or fire on heavy weight concrete properties," *Cem. Concr. Res.*, vol. 35, no. 3, pp. 590–596, 2005.
- [85] A. Nadeem, S. A. Memon, and T. Y. Lo, "Mechanical performance, durability, qualitative and quantitative analysis of microstructure of fly ash and Metakaolin mortar at elevated temperatures," *Constr. Build. Mater.*, vol. 38, pp. 338–347, 2013.
- [86] F. P. Glasser, J. Marchand, and E. Samson, "Durability of concrete—Degradation phenomena involving detrimental chemical reactions," *Cem. Concr. Res.*, vol. 38, no. 2, pp. 226–246, 2008.
- [87] O. S. B. Al-Amoudi, "Attack on plain and blended cements exposed to aggressive sulfate environments," *Cem. Concr. Compos.*, vol. 24, no. 3–4, pp. 305–316, 2002.
- [88] R. J. Flatt and G. W. Scherer, "Thermodynamics of crystallization stresses in DEF," *Cem. Concr. Res.*, vol. 38, no. 3, pp. 325–336, 2008.
- [89] B. Tian and M. D. Cohen, "Does gypsum formation during sulfate attack on concrete lead to expansion?," *Cem. Concr. Res.*, vol. 30, no. 1, pp. 117–123, 2000.

- [90] W. Müllauer, R. E. Beddoe, and D. Heinz, "Sulfate attack expansion mechanisms," *Cem. Concr. Res.*, vol. 52, pp. 208–215, 2013.
- [91] A. Hendi, A. Behravan, D. Mostofinejad, H. Akhavan Kharazian, and A. Sedaghatdoost, "Performance of two types of concrete containing waste silica sources under MgSO₄ attack evaluated by durability index," *Constr. Build. Mater.*, vol. 241, p. 118140, 2020.
- [92] S. Kawashima, P. Hou, D. J. Corr, and S. P. Shah, "Modification of cement-based materials with nanoparticles," *Cem. Concr. Compos.*, vol. 36, pp. 8–15, 2013.
- [93] Z. Guo *et al.*, "Comparison study on the sulfate attack resistivity of cement-based materials modified with nanoSiO₂ and conventional SCMs: Mechanical strength and volume stability," *Constr. Build. Mater.*, vol. 211, pp. 556–570, 2019.
- [94] P. Mondal, "Nanomechanical properties of cementitious materials." Northwestern University, 2008.
- [95] A. Hakamy, F. U. A. Shaikh, and I. M. Low, "Characteristics of nanoclay and calcined nanoclay-cement nanocomposites," *Compos. Part B Eng.*, vol. 78, pp. 174–184, 2015.
- [96] P. Hosseini, A. Afshar, B. Vafaei, A. Booshehrian, E. Molaei Raisi, and A. Esrafil, "Effects of nano-clay particles on the short-term properties of self-compacting concrete," *Eur. J. Environ. Civ. Eng.*, vol. 21, no. 2, pp. 127–147, 2017.