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Investigation of Mechanical and Thermal Performance of Nanoclay Modified Concrete for Energy Efficiency

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ABSTRACT

In recent years, the integration of Nanoclay (NC) into concrete has garnered significant global attention due to its potential added benefits and importance in the construction industry. However, the existing literature lacks sufficient experimental validation and empirical analysis pertaining to several unexplored key properties, such as thermal resistance, conductivity, diffusivity, and fire resistance. This study aims to address these knowledge gaps and contribute to the current body of literature by providing a comprehensive review of the advantageous effects of NC incorporation on the aforementioned properties of concrete. A thorough examination of available data was conducted, focusing on the mechanical and thermal characteristics of concrete after the inclusion of NC in the mix design. The findings of this critical review indicate that the incorporation of NC into concrete can reduce building energy consumption and enhance thermal insulation properties. Moreover, the integration of NC in concrete was found to improve various thermal features, including thermal stability, fire resistance, thermal performance, thermal behavior, resistance to thermal cracking, and resistance to thermal degradation. In addition, the inclusion of NC in concrete was observed to decrease thermal conductivity, thereby facilitating effective thermal insulation and resulting in lower energy consumption during heating and cooling periods. Simultaneously, the integration of NC was found to bolster the compressive, flexural, and tensile mechanical properties of concrete. Furthermore, the incorporation of NC into concrete materials has the potential to mitigate negative environmental impacts, such as pollution and poor air quality. This comprehensive review provides valuable insights into the benefits of NC integration in concrete, paving the way for further research and innovative applications in the construction industry.

1. INTRODUCTION

The rapid global population growth has led to numerous undesirable consequences on natural resources, with increasing pressures on ecological systems and infrastructure. This accelerated expansion raises concerns about the availability of essential resources for future generations, as the current rate of material consumption may not be sustainable [1-4]. The construction industry, in particular, demands a substantial volume of concrete, which can quickly deplete natural resources such as concrete, cement, sand, metals, and certain non-recyclable materials.

In response to these challenges, the international scientific community—including civil engineers, environmental experts, sustainability specialists, and other researchers—has sought to develop innovative solutions and strategies to address the issue. One such approach involves replacing conventional resources with recycled or discarded products to create more environmentally friendly construction materials [5-9]. One notable innovation in this field is the development of sustainable concrete, which aims to minimize the excessive consumption of metals and natural resources, alleviate the adverse impacts of traditional concrete, and reduce the quantity of waste materials disposed of in the environment [10-12].

The integration of waste materials into concrete has gained significant attention from scientists and civil engineering researchers worldwide in recent years [13-15]. The incorporation of certain types of waste substances in specific proportions has been found to offer numerous benefits, such as improved durability, toughness, ductility, corrosion resistance, workability, and an extended concrete lifespan. Additionally, this approach has been shown to mitigate the negative environmental impacts of traditional concrete, including the reduction of waste accumulation, pollution, and poor air quality [16-18]. Examples of waste materials employed in this sector include waste glass, waste plastic, ash, aggregate, and recyclable metals and wood [19-22].

As shown in Figure 1, Nanoclay (NC) is one such material that has been used as a replacement for cement and sand in concrete mixes. Researchers have discovered that the implementation of various recycled materials and modified waste compounds can be both environmentally and economically beneficial, as these substances can be repurposed instead of polluting natural resources and harming living organisms [23-26].

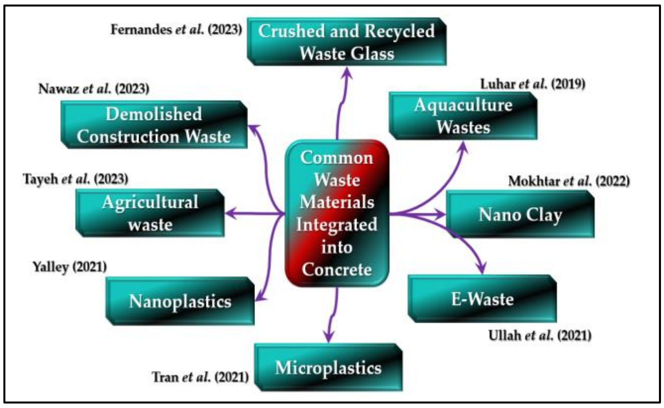

Figure 1. Common types of waste materials employed in the concrete mix to replace cement or other materials

In recent years, fibers have also emerged as a modern material incorporated into concrete, offering enhanced ductility and reduced cracking. Examples of such fibers include asbestos, rubber, glass, plastic, and bamboo [4, 23-26]. However, it has been observed that the use of specific waste categories, such as NC, can provide additional advantages and benefits to the construction industry. These benefits include optimal thermal stability, reduced energy costs for cooling and heating, and improved thermal insulation in buildings.

Despite the growing interest in NC, the current literature lacks detailed investigations and critical outcomes related to the numerous benefits of incorporating NC into concrete, including enhancements in shrinkage, water absorption, flexural strength, and compressive strength. Moreover, there is a significant dearth of experimental studies and analytical examinations concerning the thermal properties of concrete with modified NC, such as thermal resistance, thermal stability, thermal conductivity, thermal diffusivity, and fire resistance.

To address these research gaps, this paper presents a comprehensive review of the advantages of incorporating NC into concrete, focusing on the improvements in various properties of the new mix. Additionally, this review discusses the potential for reduced energy consumption and optimal environmental impacts resulting from the use of NC-modified concrete.

2. NANOTECHNOLOGY AND UNIQUE NC FEATURES

Over the last few decades, nanotechnology has emerged as a practical option for boosting the strength and durability of various construction materials with remarkable level of resilience and effectiveness. The term "nanotechnology" can be employed to describe the practice of creating and employing functional materials with a minimum of 1 nanometer (nm) to define their structural dimension within the nanoscale range. Those materials can be designed to exhibit novel properties and advanced features because their constituent particles or molecules are considerably small. Those innovative characteristics comprise biological, physical, and chemical properties. Because nanomaterials have structural dimensions from 1 to 100 nm, their physical features can remarkably vary from the physical behavior of other conventional materials. Thus, utilizing them in various construction materials could bring significant contributions and beneficial impacts for small and large-scale building enterprises and facilities [27-29].

The surfaces of nanotechnology materials, specifically NC minerals, have a one-dimensional layer structure with a thickness of 0.7 nm, corresponding to a 1:1 ratio. 1 nm corresponds to a 2:1 ratio. Those NC minerals can have several different shapes. They may be bonded to both internal and external surfaces with relative ease, and their quality can be enhanced using the exchange of ions, adsorption, and grafting techniques [30].

Recently, variant research investigations and analytical works have been executed to locate multiple potential advantages and vital novelties attained from integrating diversified categories of nanomaterials in concrete. Those nano minerals include NC, Nanohydrated Lime (NHL), Nano Silica (NS), Nanotubes (NT), Nano-sized Plastic Powders (NPP), and Nanofibers (NF) [31].

Numerous researchers found that implementing those vital minerals in concrete could provide elevated levels of temperature sensitivity, enhanced strain resistance, considerable ductility, less electrical resistivity, and more significant surface area [32, 33].

At the same time, some scholars, like Sarsam [34]; Yang and Tighe [29], affirmed that utilizing nanomaterials in asphalt concrete, such as NS, by percentages from 1% to 2% could foster antistripping properties, anti-aging features, fatigue cracking resistance, and rutting resistance. Furthermore, those authors found that incorporating 1% to 2% of NS could boost the asphalt cement consistency and elaborate temperature susceptibility and elastic strain recovery.

Moreover, Mokhtar et al. reported variant advantageous effects and positive features in the mechanical behavior and durability features fulfilled in the new concrete mix after integrating some percentages of different nanomaterials, such as Nano-Alumina (NA), Nanoplastics (NPs), Carbon Nanotubes (CNTs), Carbon Nanofibers (CNFs), NS, and other classifications of nanoparticles [35-42].

Regarding the critical NC features, scholars noted that NC could be characterized by its sheet-based nano-dimension white molecules with a mean particle dimension between approximately 50 and 100 nm.

Besides, NC has a specific surface area between roughly 90 and 800 m^2/g. NC's aspect ratio varies from 200 to 1,000 for most engineering applications. The specific gravity of NC material differs from 2.4 to 2.6. Concurrently, its density equals 1,980 kg/m^3 [43, 44].

Table 1. Vital chemical compositions and their names in NC, NNT [45]

No.	Chemical Compound	Name
1	Talc	$Mg_3[Si_4O_{10}(OH)_2]$
2	Mica	$KAl_2[AlSi_3O_{10}(OH)_2]$
3	Kaolin	$Al_2[Si_2O_5(OH)_4]$
4	Montmorillonite	$Mg_{0.33}Al_{1.67}[Si_4O_{10}(OH)_2](Ca, Na)_x (H2O)_n$
5	Serpentine	$Mg_3[Si_2O_5(OH)_4]$
6	Sepiolite	$Mg_4[Si_6O_{15}](OH)_2.4H_2O$

NC is composed mainly of phyllosilicates which consist of a group of minerals, including (A) Talc, (B) Mica, (C) Kaolin, (D) Montmorillonite, (E) Serpentine, and / or (F) Sepiolite.

Table 1 describes the chemical compositions and names of those compounds. Building on the compound names mentioned in Table 1, Aljbouri and Albayati [46] clarified that the most significant ratio of chemical molecules existing in NC is SiO_2, corresponding to a percentage of 50.95%, followed by Al_2O_3, which has a proportion of 19.60%.

Furthermore, NC has other compounds, like Na_2O, MgO, K_2O, CaO, TiO_2, and Fe_2O_3, with content ratios of 0.98%, 3.29%, 0.86%, 1.97%, 0.62%, and 5.62%, respecitvely.

On the other hand, NC is renowned for having lesser flammability and significant fire resistance. This exceptional property could offer further advantages in the construction sector, reflected in elevating the ability of concrete and cement materials to withstand elevated fire attacks and more significant thermal loading.

The typical chemical composition of NC is depicted in Figure 2.

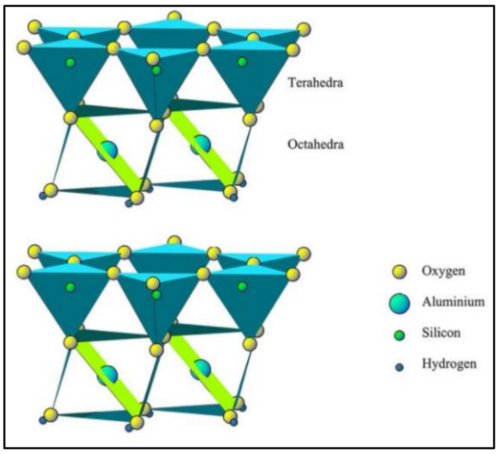

Figure 2. Chemical structure of NC mineral [47]

Table 2. Physical properties of NC [46, 48, 49]

No.	Property	Value
1	Moisture/Humidity content	1% to 2%
2	Loose bulk density	227 kg/m^3
3	Weight loss via ignition	39%
4	X-Ray results	19.1 Å (for d_{001})
5	Type of mineralization	Montmorillonite
6	Surface area	266 m^2/g
7	Electrical conductivity (siemens/ meter)	−25 S/m
8	Ion exchange coefficient	48
9	Color	Pale yellow
10	Specific gravity	3.6

NC's unique characteristics distinguish this compound from other materials and minerals due to its enhanced chemical, physical, and mechanical merits.

Concerning the substantial physical properties connected with this compound, Table 2 is developed to provide a summary of NC's physical features.

Various researchers depend on Scanning Electron Microscope (SEM) investigations to detect the microstructure of the new concrete mix, which contains some ratios NC.

For instance, SEM images were recorded for Self-Compacting Concrete (SCC) comprising 2% of NC, as expressed in Figure 3.

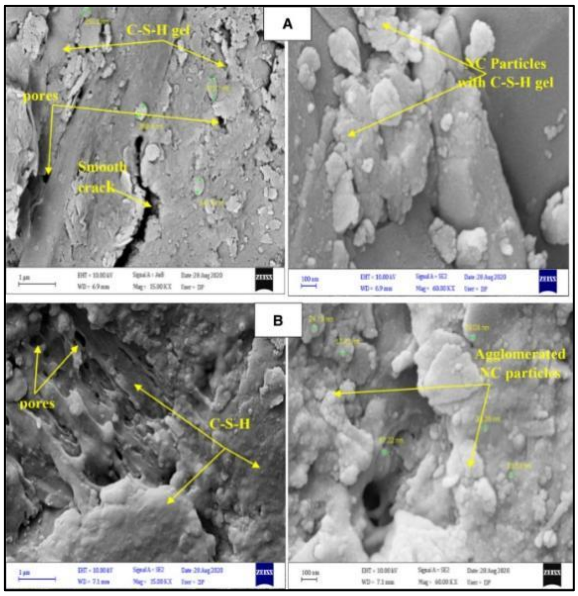

Figure 3. SEM images of SCC with 2% of NC at (a) an age of 56 days and (b) an age of 120 days [50]

Meantime, the leading mechanical properties of NC based on tensile strength, modulus, failure strain, and toughness can be illustrated in Table 3.

Table 3. The major mechanical characteristics according to various NC ratios [48].

#	NC (Percent Weight)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Failure Strain (%)	Toughness (MJ/m^3)
1	0%	139.80	8.20	1.80	1.30
2	3%	175.50	9.20	2.00	1.90
3	5%	144.60	7.80	1.90	1.40
4	7%	133.70	8.20	1.70	1.10
5	10%	54.80	3.50	1.70	0.50

3. INFLUENCES OF NC ON CONCRETE'S MECHANICAL PROPERTIES

Research on concrete's mechanical properties is an interesting theme on which several scholars worldwide were motivated and enthusiastic about conducting analysis.

When NC is employed in concrete, some benefits can be attained, like enhanced workability, significant resistance to water absorption, decreased permeability and decreased porosity. Common content percentages implemented for NC replacement include 2%, 4%, 6%, 8%, 10%, 12%, 14%, and 15% [51]. However, some authors mentioned the use of more than 15% in concrete [52-54].

Simultaneously, other scientists reported some relevant added values and important characteristics that were observed after some proportions of NC mineral were involved in the concrete design mix. For example, those researchers noticed that mechanical properties, durability, compressive and / or tensile strengths, long-term strength, and microstructure had some kinds of enhancements and elaborations, helping make the new concrete mix more robust and servable for various construction purposes [42, 55-58].

There are some categories of parameters and critical variables in concrete that can appropriately define its mechanical behavior and mechanical performance. Those vital variables include compressive strength, splitting tensile strength, flexural strength, toughness, impact strength, and durability. When specific types of materials are incorporated into the concrete design mix, those crucial mechanical properties may be influenced by either significant enhancements or weakening.

Scientists, including Wang [59] and Mehrabi et al. [60], inspected the major benefits of NC utilization in the building sector. They reported that this innovative material is distinguished by its greater resilience and tensile strength. These characteristics make it possible to incorporate into concrete for various structural applications requiring greater strength and toughness. Additionally, NC's enhanced corrosion and abrasion features are significant. Those boosted properties in NC can be used in construction to help concrete serve under challenging working circumstances.

Mansi et al. [51] explored the effect of using NC in concrete to enhance different aspects of its workability and mechanical properties. The research methodology used by the scholars relied on a thorough assessment of the literature that addressed a variety of NC characteristics, critical physical and chemical properties, and NC role in concrete. They reviewed various recent articles and applied a secondary data strategy to gather their data. Their thorough research confirmed the importance of using NC in the construction sector, especially for concrete. The reason was its considerable potential to promote the concrete's mechanical properties, namely enhancements in water absorption, durability, permeability, compressive strength, and flexural strength.

Shakrani et al. [61] managed an analytical work identifying numerous advantageous and multiple preferable influences in the Pervious Concrete Pavement (PCP) when specific volumes of NC are engaged and incorporated into the new PCP design mix. They explained that in the last few decades, nanotechnology has emerged as a practical option for dramatically boosting the strength and durability of building materials. This concept is used to describe the practice of creating and employing functional structures with at least 1 nm. Those materials can be designed to bring novel properties because their constituent particles or molecules are so small. Those innovative features and favorable added values comprise physical features, mechanical behavior, durability performance, and enhanced microstructure effectiveness. They added that NC application in pavement technology and various construction projects has recorded an increased interest and attention levels in recent years due to its beneficial potential in fostering diversified properties of construction materials. Furthermore, based on their overview analysis, it was determined that the involvement of NC in pervious concrete as a cement replacement helped elaborate the performance of pavement projects. Concurrently, reinforcements in diverse strength properties like compressive and flexural strength, durabilities like freeze-thaw and chloride penetration resistance, shrinkage, and denser microstructure were observed after NC was integrated into the pervious concrete mix. In contrast, porosity, permeability, and water absorption features declined.

3.1 Favorable effects of NC on concrete's durability and workability

Various researchers, including Mansi et al. [51], Brightson et al. [54], Dungca et al. [56], Hussain et al. [62], Tang et al. [63], Alharbi et al. [64], Sonebi et al. [65], Tayeh et al. [66], Wang et al. [67], reported that adding NC to concrete would provide more enhancements in terms of its durability, mechanical properties (like strength and hardness), and workability, besides its major advantage of offering more sustainable concrete.

The primary reasons for those enhancements are because of the intelligent mechanisms brought by the integration of NC into the concrete, through which significant amendments in the microstructure and remarkable minimization of pores and voids could be attained [68]. At the same time, nanoparticle addition into concrete could help maximize considerable loading durability as those cutting-edge minerals could act as bridges across cracks and voids, ensuring a load transfer in the tension case.

Consequently, scholars estimated the impact of NC on concrete's energy consumption and energy cost savings, reflected in optimum elaborations on the concrete's thermal properties. They found that adding specific percentages of NC into concrete would increase its thermal resistance and thermal stability, which can help make concrete more energy efficient, as thermal losses across concrete slabs, walls, ceilings, and walls can be mitigated [20, 69-71].

Niu et al. [52] reported that increased concrete thermal insulation is a crucial mechanical and thermal change. NC particles improve concrete's resistance to water and reduce its capacity to absorb moisture. Additionally, concrete's practical thermal qualities, such as its resistance to larger thermal loads, are one of the benefits of adding NC. Concrete's flexural strength, compressive strength, and durability can all be improved by utilizing NC.

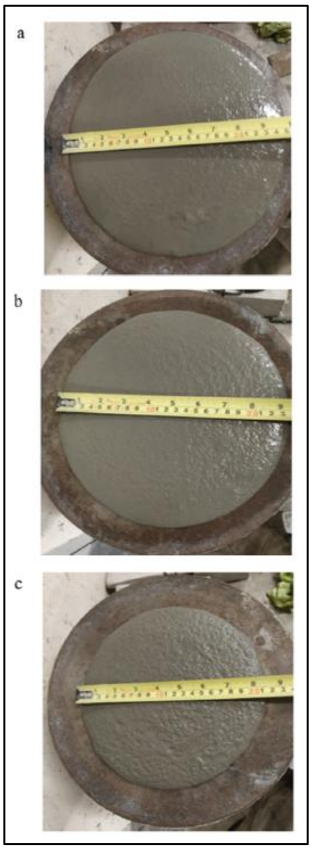

Figure 4. Workability assessment via slump test of NC integration into concrete: Slump radius is reduced with elevated ratios of NC. (a) NC=0.0 kg/m^3, (b) NC=3.0 kg/m^3, and (c) NC=6.0 kg/m^3 [72]

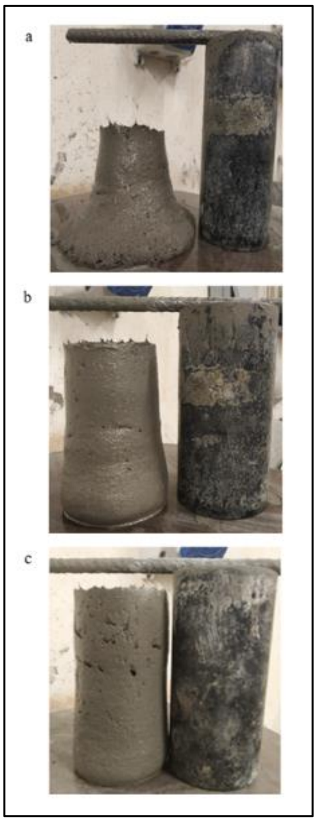

Figure 5. Other workability evaluation methods of slump test via elevation of concrete mixes containing NC quantities of (a) NC=0.0 kg/m^3, (b) NC=3.0 kg/m^3, and (c) NC=6.0 kg/m^3 [72]

Mousavi et al. [73] led an analysis exploring the effects of replacing part of cement with NC on concrete's performance and mechanical and thermal characteristics. They used a thorough examination of the literature. They gathered secondary data from different peer-reviewed papers to meet their research objectives. Their research of the available literature supported the notion that adding NC to concrete increases its compressive strength and lowers shrinkage. In addition to the NC contributions, it was determined that concrete thermal properties could be boosted, making buildings consume less electrical power and lower cooling and heating energy rates.

Proofs of workability enhancements are expressed in Figure 4. This figure shows the estimation of concrete's workability after adding some portions of NC.

In addition, Figure 5 indicates another evidence of elaborations conducted on the concrete mix after specific quantities of NC were taken into account.

Besides, Niu et al. [52] identified significant alterations and beneficial aspects of NC and calcined NC use in concrete on its thermal and mechanical properties. Those authors adopted the secondary data collection strategy. The replacement of NC and calcined NC in concrete and the effect of this replacement was reviewed in several academic and popular publications. According to their review findings of the review analysis, NC and calcined nano-clay have more muscular pozzolanic activity. Additionally, the review's findings showed that adding NC to concrete can enhance its workability and mechanical qualities while reducing shrinkage and hydration resistance. These advantageous effects depend on the barrier, bridging, nucleation, pozzolanic, and filling effects of NC and calcined NC.

Some statistical data describing the impact of NC on concrete's workability are depicted in Figure 6.

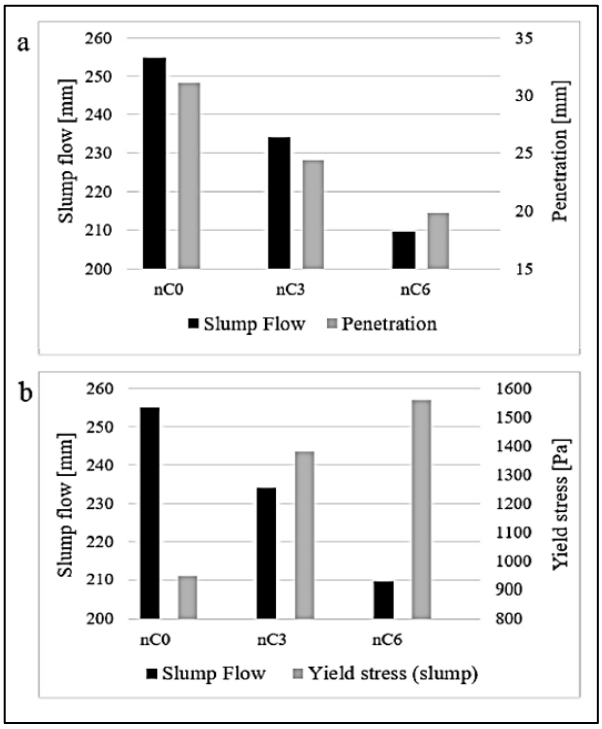

Figure 6. Slump flow characteristics, penetration, and static yield stress statistical findings based on the integration of NC in concrete: (a) NC=0.0 kg/m^3, (b) NC=3.0 kg/m^3, and (c) NC=6.0 kg/m^3, [72]

It can be inferred from Figure 6 that slump flow would decrease with elevated quantities of NC. In contrast, significant rises in the static yield stress could be noted with higher amounts of NC.

Hamed et al. [53] studied how adding NC to concrete impacts the material's mechanical and thermal properties. They conducted an experimental process to foretell the new properties of concrete after adding NC. The concrete contains 5%, 7.5%, and 10% of NC as partial replacement ratios. There used two ways to apply these three percentages. In the first method, NC is introduced without the water being altered. These three percentages are involved in the second method after the concrete has been dissolved in water using a bath sonicator. The authors then examined the properties of concrete, such as slipping bond stress, flexural strength, split tensile stress, and compressive strength. The micro- and nanostructure and properties of concrete after the addition of NC were predicted using scanning electron microscopy images, X-ray diffraction analyses, and atomic force microscope images. According to the results of the laboratory tests, sonicating nano-clay particles in concrete significantly improved its qualities compared to nano-clay concrete without sonication. Additionally, it was discovered that 7.5% was the ideal NC proportion for improved and optimized concrete properties.

4. IMPACTS OF NC ON THERMAL PROPERTIES

Construction professionals and scientists did not focus only on the mechanical properties of new concrete mixes after particular proportions of NC were added. Though, they also concentrated on other vital structural features that could be elaborated to help make construction facilities and buildings more ecologically sustainable and thermally stable and efficient. Those necessary aspects could achieve satisfactory impacts and compatible properties in terms of lower energy consumption and cheaper electrical bills because of active energy-saving elaborations attained after the utilization of NC. The thermal properties associated with these crucial concepts embrace thermal conductivity, energy performance, energy stability, heat capacity, thermal diffusivity, thermal resistance, and extreme thermal loading resistance (fire resistance potential).

A variety of academics and engineers shed light on the crucial role and various positive impacts of using NC in concrete to improve its thermal properties and thermic effectiveness in concrete. Researchers discovered that adding NC to concrete could enhance its thermal resistance, fire resistance, and some of its mechanical properties, including splitting tensile, flexural, and compressive strengths. These amendments in the thermal properties could improve concrete's resistance to higher thermal loads and sulfate attacks. Also, it could make it more profitable in terms of optimum energy consumption and thermal insulation in the building under various demanding conditions.

Additionally, several researchers estimated multiple mechanical properties in concrete after replacing some portion of cement [21, 67, 74-93].

Those authors added that the low thermal expansion of NC is another noteworthy characteristic that could be attained from integrating NC into concrete. When larger thermal loads are applied, materials produced from NC or containing a specific percentage of NC are thermally stable. They cannot be altered or changed shape. Utilizing NC in concrete and building materials is notable for enabling superior and significant surface quality and finish, besides its contribution to enhancing thermal insulation rate.

NC has considerable resistance to higher flammability rates. Thus, it is exceptionally resistant to fire and a good insulator. Additionally, this study identifies some articles and their findings regarding the effect of NC on concrete's thermal properties.

Irshidat and Al-Saleh [69] wrote a paper in which they discuss some of the thermal properties exhibited by the concrete following the addition of NC. In addition, they discussed the thermal performance and fire resistance to fire that NC-modified concrete possessed. To make the modified mortar mix, some of the cement was substituted with montmorillonite NC, with the replacement percentage ranging from 0 to 2% based on the weight of the cement. Following an incubation period of 28 days, specimens of the hardened mortar were subjected to high temperatures of 200°C, 400°C, and 600°C for a duration of two hours each. In order to investigate the thermal performance of the NC-modified specimens, tests utilizing differential scanning calorimetry and thermogravimetric analysis were carried out. A comparison was made between the residual mechanical strengths of heated specimens and the strengths of control specimens to determine the material's fire resistance. X-ray diffraction and scanning electron microscopy tests were used to evaluate the influence of NC on the chemical composition and microstructure of heat-damaged specimens. Both of these tests were performed on the damaged specimens. According to the findings of the experiments, the compressive, tensile, and flexural strengths of the NC modified cement mortar are much greater than those of the control specimens, particularly at higher temperatures. Incorporating NC considerably slowed down the deterioration in tensile and flexural strengths of cement mortar that was brought on by prolonged exposure to high temperatures. Images obtained using a scanning electron microscope revealed that the presence of NC reduced the density and width of the hairline cracks that manifested along the cement matrix after being subjected to elevated temperatures. When it comes to the findings of the thermal properties assessment, it was discovered that the use of NC enhanced both the thermal performance and fire resistance of the concrete.

Rooholamini et al. [94] wrote research in which they discussed various thermal properties that occur in concrete following the use of NC. In addition, they discussed the thermal performance and fire resistance to fire that NC-modified concrete possessed. The researchers also looked into how NC and its combination with styrene-butadiene-styrene (SBS) affected the fatigue behavior of hot mix asphalt and concrete. When it came to the four-point beam fatigue and the indirect resilient modulus at low and mid temperatures, pairwise comparisons were carried out using both aged and unaged modified specimens. These specimens included 6% NC, 6% SBS, 2% NC, +4% SBS, 4% NC, and +2% SBS. In addition, the midpoint temperature of 25 degrees Celsius was used for the indirect tensile strength test. According to the findings, NC improved both the fatigue resistance and certain thermal properties, such as the aged and unaged mixture's resistance to thermal cracking. At low temperatures, it was discovered that SBS and NC have a detrimental effect on the material's fatigue life and thermal cracking. In addition, it was demonstrated that the addition of NC improved the fatigue performance of the SBS-modified mixes when the temperature was in the middle.

Guo et al. [95] investigated a number of the thermal parameters of the concrete following the use of NC. In addition to that, they discussed the thermal performance associated with NC concrete. According to what they found, recent developments in material technology have encouraged the result of various preparation processes and applications of innovative polymer-NC composites. New polymer-NC composites with improved properties have been successfully incorporated in various industries, including automobile, petroleum, aerospace, construction, wastewater treatment, and biomedical applications, due to the development of novel synthesis pathways that have led to the creation of these composites. Because of their excellent qualities, such as improved density and strength, relatively large surface areas, high elastic modulus, flame retardancy, and thermomechanical / optoelectronic / magnetic capabilities. These composites are acknowledged as potential advanced materials. The authors carried out an extensive review, identifying important benefits and significant implications of employing NC in the concentrate on the basis of its thermal and mechanical properties. They concluded that incorporating NC into concrete would change and improve the material's resistance to heat and fire and its other thermomechanical qualities. Additionally, it was discovered that incorporating NC into concrete could improve the material's strength, density, and elastomeric modulus. Table 4 summarizes the major contributions and relevance of these research papers addressed in section 3.1.

Niaki et al. [20] discussed the thermal performance and the resistance to fire that NC modified concrete. The authors described the investigation into the synthesis and improvement of the mechanical properties and thermal features of utilizing clay nanoparticles and basalt fiber in concrete to modify and enhance both its thermal and mechanical properties. This was done in order to improve the mechanical properties of concrete. Experiments were performed to determine, first, how the addition of chopped basalt fiber affected the compressive, flexural, splitting tensile, and impact strengths of the concrete, as well as how the effect of varying temperatures (up to 250℃) affected the strength of the concrete. As a result of their research, it was found that the addition of basalt fiber to concrete enhanced its mechanical and thermal qualities, as well as its capacity to resist temperature changes. Experiments were carried out to investigate the impact that NC particles had on the mechanical properties of the concrete, as well as the impact that high temperatures (up to 250 degrees Celsius) had on the strength of the concrete. It was discovered that incorporating NC into material will result in an increase in the impact, flexural, and compressive strengths. In addition, improvements would be made to the thermal qualities, particularly the thermal stability. However, this would result in a decrease in the tensile strength of the concrete. In order to investigate the fracture surface and morphology of several different concrete specimens, an SEM examination was carried out. As a consequence of analyzing the SEM pictures, it was found that using NC would produce polymer concrete that is not only lightweight but also possesses increased levels of thermal stability, thermal performance, and mechanical strength.

Table 4. The critical benefits of harnessing recycled plastics in concrete to improve its thermal properties

Reference	Type of Thermal Properties						Other Thermal Characteristics
	Thermal Conductivity	Thermal Insulation	Fire Resistance	Thermal Resistance	Thermal Diffusivity	Thermal Stability	
[20]				×		×	---
[69]	×		×			×	Thermal performance and thermal behavior
[94]							Thermal cracking resistance
[95]			×			×	Thermal degradation resistance, thermal behavior, and creep resistance

5. CONCLUSIONS AND FUTURE SUGGESTIONS

5.1 Conclusions

This study is carried out to investigate the critical relevance and benefits of using NC in concrete on its mechanical properties, thermal properties, and energy consumption. The research relied on a comprehensive review to achieve the work goals. The extensive review shed light on concrete's different mechanical and thermal properties after the NC was integrated into concrete.

In addition, the thorough review highlighted the effect of NC use in concrete to reduce energy consumption in buildings. There is a shortage of publications that investigate the contribution of NC on concrete's thermal performance and mechanical properties. Thus, this research tries to fill this research gap.

According to the comprehensive review, the results of this work can be summarized in the following paragraphs:

(1) NC utilization in concrete provided different functional improvements in its thermal properties (like thermal stability, fire resistance, thermal performance, thermal behavior, thermal cracking resistance, and thermal degradation resistance).

(2) Implementing NC in concrete contributed to active and feasible thermal insulation and optimum energy consumption due to the significant decline in the thermal conductivity of the new concrete mix.

(3) Energy bills of summer and winter cooling and heating loads could be minimized due to the considerable decrease in the concrete's thermal conductivity.

(4) NC integration into concrete offered some benefits in terms of mechanical properties, namely durability, workability, impact strnegth, compressive strength, flexural strength, and tensile strength.

(5) Employing NC in concrete could also contribute to some valuable merits for nature and sustainability, like the reduction of environmental pollution due to the lower consumption of fossil fuel energy and the replacement of ecologically severe materials.

5.2 Future work

It is crucial to follow a group of guidelines and futuristic aspects whose adoption could expand the knowledge and research work pertaining to the critical advantages and valuable rationales of NC in concrete. Those future work suggestions include the following points:

(1) To lead further experimental analysis connected with the NC's relevant functionality and practical efficiency in boosting the effectiveness and mechanical behavior of concrete.

(2) To implement those research steps not only on conventional concrete but also for pervious concrete, SCC, and Ultra-High Performance Concrete (UHPC).

(3) To include more testing methods and validation techniques with the help of laboratory inspections to provide further statistical database and numeric figures to facilitate the comparative analysis of concrete with and with no NC.

5.3 Research limitations

Despite the successful accomplishment of the thorough review related to the importance of NC and its essential relevances in modifying and enhancing concrete's mechanical and thermal properties, this paper encountered some constraints and challenges that limit the comprehensive implementation of this extensive overview. Those limitations include the following aspects:

(1) Not all research articles conducted an entire analysis covering all properties of concrete after NC was added.

(2) Few research publications did address the advantageous contributions and rationales of NC in concrete connected with added values of energy savings and thermal performance of concrete, especially during cooling and heating seasons.

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