International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 47, No. 5, October, 2023, pp. 341-350
Journal homepage: http://iieta.org/journals/acsm

Investigating the Mechanical and Thermal Properties of Concrete with Recycled Nanoplastics for Enhanced Sustainability

Zaid Abbas Jassam[1], Fathoni Usman[2], Gasim Hayder[3,4], Yasir Al-Ani[5*]

[1] College of Graduate Studies, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[2] Institute of Energy Infrastructure, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[3] Institute of Energy Infrastructure (IEI), Universiti Tenaga Nasional (UNITEN), Kajang 43000, Selangor Darul Ehsan, Malaysia
[4] Civil Engineering Department, College of Enineering, Universiti Tenaga Nasional (UNITEN), Kajang 43000, Selangor Darul Ehsan, Malaysia
[5] Department of Dams & Water Resources Engineering, College of Engineering, University of Anbar, Ramadi 31001, Anbar Province, Iraq

Corresponding Author Email: aniyaser@uoanbar.edu.iq

https://doi.org/10.18280/acsm.470508

Received: 6 April 2023
Revised: 8 June 2023
Accepted: 15 June 2023
Available online: 31 October 2023

Keywords:
concrete, thermal properties, mechanical properties, nano plastics, recycled plastic waste, environmental influence, sustainability, green concrete, energy efficiency

ABSTRACT

Over recent decades, the concrete industry has experienced significant advancements, including the incorporation of recycled waste materials to enhance sustainability and various properties. However, the current literature lacks comprehensive investigations regarding the critical contributions and benefits of Nanoplastics (NPs) in improving concrete's mechanical and thermal properties, such as tensile strength, compressive strength, splitting strength, and thermal characteristics, including thermal stability and insulation. This study aims to investigate the valuable effects of integrating waste materials, particularly NPs, into concrete and to elucidate the impact of NPs on concrete's mechanical and thermal properties. Furthermore, this paper seeks to highlight the positive environmental implications of using NPs in concrete. A comprehensive literature review was conducted to address these aspects and achieve the research objectives. Academic peer-reviewed articles and recently published papers were examined to discuss the practicality and various essential benefits of incorporating NPs into the concrete mix. The review revealed that the use of NPs in concrete leads to improvements in mechanical properties, such as shrinkage, splitting tensile strength, compressive strength, shear resistance, and flexural strength. Simultaneously, the substitution of various NP ratios in concrete enhances thermal resistance, contributing to more energy-efficient structures due to the substantial thermal insulation provided by the plastic incorporation. With respect to environmental aspects, employing waste materials renders the concrete more sustainable, eco-friendly, and cost-effective compared to conventional concrete. Based on the thorough review conducted, which demonstrated the advantageous effects of NPs on concrete performance concerning mechanical, thermal, and ecological measures, it is crucial to expand the available literature on the beneficial evaluations of NPs' contributions to the efficacy and practicality of the concrete mix.

1. INTRODUCTION

In recent years, scholars and construction professionals have investigated critical concepts and definitions associated with the adverse consequences of the construction industry. These significant notations are related to (I) environmental impact and (II) resource depletion. Regrettably, the building sector has contributed to undesirable impacts on the environment and future generations [1]. For instance, utility-scale enterprises and large-scale infrastructure projects have led to excessive consumption of metals, natural resources, and vital elements and materials on the planet. As an indispensable building material, concrete also has a high ecological footprint, potentially polluting the environment during the manufacturing and preparation processes of sand, cement, and other essential components [2-5].

In response to these serious issues and concerns, numerous scholars, ecological consultants, and civil engineering specialists from developed and developing countries have conducted extensive analytical works and laboratory surveys to seek strategic solutions and feasible approaches to mitigate the negative influences of construction activities on future generations [6, 7]. Researchers have explored various techniques to make concrete more environmentally friendly and sustainable. One such approach is sustainable concrete, in which depleted substances and waste materials can be recycled and modified, contributing to the following gains:

A. Alleviating the accumulation of extravagant quantities of waste and exhausted substances on lands and oceans,

B. Minimizing the pace of air pollution and dramatic decline in ecological quality,

C. Investing some wastes in concrete preparation to help provide further advantages, such as elaborations on its mechanical and thermal features and mitigation of its harmful environmental impacts.

Some scholars have suggested replacing partial ratios of sand or cement in concrete, while others have evaluated the opportunity and influences when the entire sand or cement component is substituted with waste materials (e.g., glass waste, silica fumes, rice husk ash, fly ashes, and slags) [8-11]. In both scenarios, significant changes and favorable amendments in concrete features have been observed, including enhancements in mechanical properties and considerable elaboration in thermal characteristics.

Waste Plastic (WP) has gained popularity as a universally prevalent material in recent decades [12-15]. Engineers and researchers have been enthusiastic about the positive impacts and advantageous relevances achieved after incorporating specific proportions of WPs in new concrete mixes. The recycling and recovery of WP and discarded plastics for use in concrete have been widely adopted worldwide, fostering improvements in concrete's thermal and mechanical characteristics, specifically minimizing thermal conductivity, enhancing workability, and compressive strength [16-20].

These upgraded features can be attributed to the practical traits and feasible qualities of plastics, which are efficient thermal insulators (with a thermal conductivity ranging from 0.025 to 0.17 W/m.K) [21]. Consequently, concrete containing these materials becomes more efficient and substantially convenient for use during winter and summer, as the thermal loading of cooling and heating is retained within the facility's envelope, contributing to reduced electrical bills and energy requirements due to active insulation of walls, ceilings, floors, roofs, and other building parts [22-27].

A comprehensive review of the available literature reveals that numerous publications have investigated the practical workability of new concrete mixes containing specific ratios of WPs. However, certain types of WPs, notably Nanoplastics (NPs), have been rarely analyzed and mentioned. WPs are generally processed and handled based on four major principles, as described in Figure 1.

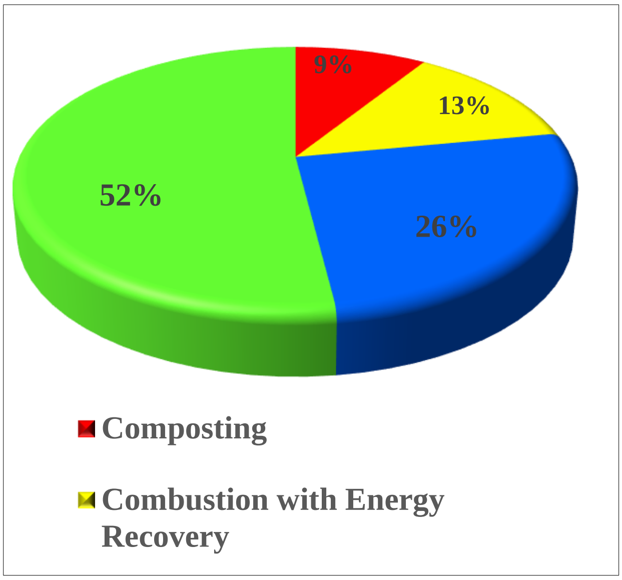

Figure 1. How WPs are handled worldwide [28]

Simultaneously, the worldwide increase in plastic production has grown dramatically, as illustrated in Figure 2. It is essential to emphasize the severe environmental pollution concerns globally due to the extensive use of plastics and the inadequate recycling techniques adopted [29-35]. The statistics in Figure 2 underscore the need for concerted efforts and approaches to address the escalating growth of WP quantities annually.

Plastics can generally be classified based on their size. Table 1 provides a detailed categorization of plastic types according to their dimensions. Furthermore, it has been determined that replacing cement or sand with WP, Microplastics (MPs), or NPs can enhance concrete's mechanical properties [28]. These mechanical feature enhancements include amendments in shrinkage, compressive strength, and shear resistance.

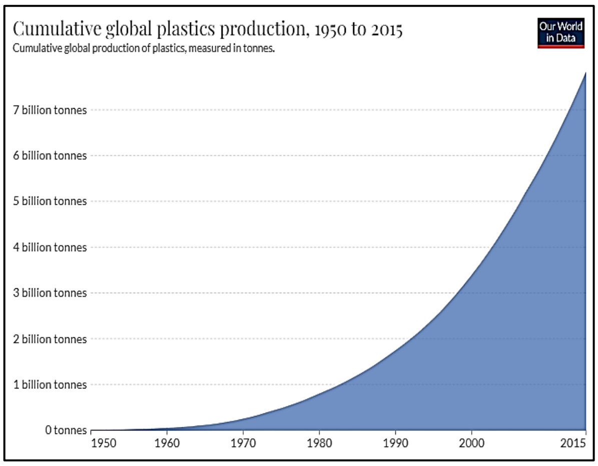

Figure 2. The cumulative plastic production on the planet [36]

Table 1. The major categories of plastics depending on their size [28]

No.	Plastic Classification	Particle Size/Diameter
1	NPs	Less than 0.0001 mm
2	Small microplastics	From 0.0001 to 1 mm
3	Large microplastics	Between 1 and 4.75 mm
4	Meso-plastics	4.76 to 200 mm
5	Macro-plastics	More than 200 mm

Experimental analyses have revealed that adding portions of waste plastic in concrete positively affects the splitting tensile strength properties, making concrete more practical and robust for large-scale construction purposes and utility building projects [37-43]. Simultaneously, some scientists have investigated using and replacing WP in the concrete mix, discovering that replacing different ratios of waste plastic with cement or sand can consolidate the concrete structure, improving its flexural strength [44-46].

Despite these findings, recent and earlier peer-reviewed articles, conference proceedings, and graduate theses remarkably lack investigations and analytical studies exploring concrete's mechanical and thermal properties after the integration of NP waste materials [47-52]. This study aims to bridge these research gaps and fill the knowledge gap linked to the adoption of NP waste in concrete preparation.

2. SUBSTANTIAL PROPERTIES OF NANOPLASTICS AND PLASTICS

Adding waste plastic concrete into concrete would provide some beneficial influences and practical relevances due to its properties that differ from sand and cement. Table 2 explains some critical properties of waste plastic compared with sand and cement, Warsito and Triadi Putranto [53]; Zhang et al. [54]; Puluhulawa and Puluhulawa [55].

Concurrently, the tensile strength values of concrete are more significant than sand and cement. Thus, it is predicted that experimental analysis and investigations could reveal that using NPs and waste plastic material will enhance concrete's strength, durability, and robustness, Almohana et al. [56]; Deraman et al. [57]; Haque and Islam [58]; Abah et al. [59]; Faraj et al. [60]; Vakhshouri and Nejadi [61]; Fernando et al. [62].

Table 2 provides a set of thermal and physical properties linked to WP/ NP with comparative data connected with sand and cement.

Table 2. Some thermal and physical properties of WP/ NP compared with sand and cement, Contreras et al. [63]; Roque et al. [64]; Guendouz et al. [65]

No.	Property	WP/ NP Powder	Sand	Cement
1	Apparent Density	350 kg/m^3	1,400 kg/m^3	1,440 kg/m^3
2	Bulk Density	450 kg/m^3	2,560 kg/m^3	1,030 kg/m^3
3	Water Absorption	≈ 0%	2.66%	5.5% to 6.5%
4	Thermal Conductivity	0.1 to 0.3 W/m.K	0.25 W/m.K	1.55 W/m.K
5	Porosity	30–75%, H/D ratio (0.5 – 2.0)	0.45%	48.5% to 68.8%
6	Tensile Strength	55 MPa (Polyethylene Terephthalate)	1,416 Pa (Fine Sand)	3.50 MPa

It can be inferred from Table 2 that the thermal conductivity of plastic/ NPs is lower than sand and cement. Therefore, replacing large portions (i.e. more than 10%) of sand or cement would offer beneficial solutions for concrete concerning its thermal stability and thermal insulation. It is vital to remark that bulk density, mentioned in this table, differs from the apparent density by excluding pores and voids in the sand/ plastic powder. Moreover, the value of porosity related to the cement (which is 48.5% to 68.8%) was calculated based on a water-to-cement ratio of 0.30 to 0.70.

Meantime, it is indicated in Table 2 that the porosity of plastic is remarkably low compared with sand and cement. Hence, utilizing waste plastic in concrete could make concrete more practical in restricting the quantity of water that might result in failure due to cyclic salt attacks and freeze-thaw cycles.

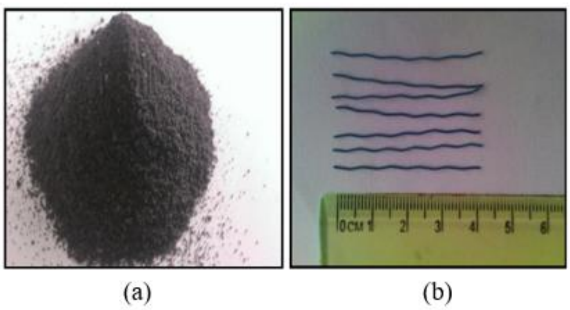

Figure 3. Images of (a) plastic powder and (b) plastic fiber, Guendouz et al. [65]

The levels of contributions and elaborations related to plastic fiber (Figure 3 b) would differ from waste plastic powder, shown in subgraph (a) of Figure 3. Though, both plastic fibers and plastic powders are substantial in bringing some practical relevances and active advantages in concrete.

To provide further illustration regarding the variation between the waste plastic fiber and waste plastic powder effects on the concrete mix, Figures 2 and 3 represent some details on the mechanical properties enhancements attained by the incorporation of WP in concrete. Figure 2 addresses the flexural strength (in MPa) improvement with the help of plastic powder.

To provide more illustration regarding the variation between the waste plastic fiber and waste plastic powder effects on the concrete mix, Figures 2 and 3 represent some details on the mechanical properties enhanced by waste plastic. Figure 4 addresses the flexural strength (in MPa) improvement with the help of plastic powder.

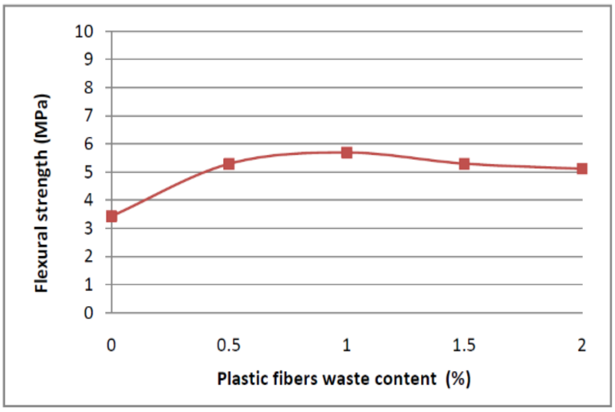

Figure 4. Flexural strength variation with plastic powder employment in the concrete mix, Guendouz et al. [65]

On the other hand, Figure 5 describes the flexural strength profile associated with WP integration into concrete.

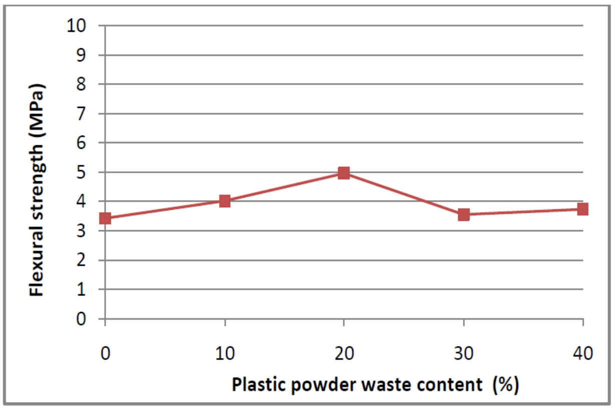

Figure 5. Flexural strength variation with plastic fiber integration into the concrete mix, Guendouz et al. [65]

It can be inferred from Figures 4 and 5 that using WP material in concrete would attain a maximum flexural strength of approximately 5 to 5.5 MPa. Nonetheless, the percentage of plastic fiber used in concrete ranges between 0.50% and 2%. In comparison, utilizing 10% to 40% of WP in concrete would achieve roughly the same flexural strength values in the new concrete mix after adding WP material.

3. IMPACTS OF RECYCLED NANOPLASTICS ON CONCRETE'S MECHANICAL PROPERTIES

The compressive strength, tensile strength, elasticity modulus, and other critical properties were addressed by variant scholars who evaluated the impacts of WP integration into concrete. For instance, Yalley [66] found that employing specific ratios of WP by replacing some portions of sand or cement could provide some enhancements in the concrete's corrosion resistance and bond strength. Ahdal et al. [67] also discovered that significant elaborations could be attained, reflected in enhancing compressive strength via WP. Furthermore, voids, water absorption, and cavities in concrete would be elaborated after particular ratios of WP were employed, Karimipour [68]; Pereira et al. [69]; Dafalla et al. [70].

Moreover, Lamba et al. [28] mentioned that after integrating some proportions of WPs into concrete, observations on enhancements of compressive and flexural strengths of concrete were recorded. The types of WP harnessed in their work contained recycled polypropylene, high-density polyethylene, and high-density polythene.

Besides, a study was conducted by Massachusetts Institute of Technology (MIT) students to examine the use of WP and its significant environmental impacts on concrete and the corresponding influences of recycled WPs on concrete properties. The scholars created concrete and made several replacement ratios following analytical and experimental processes. They also estimated the contribution of using recycled WP to the minimization of carbon dioxide emissions. The students realized that replacing some cement components with fine recycled WP powder could offer a concrete mix that is 15% more resilient and powerful (in terms of compressive strength) than conventional concrete. This was accomplished by subjecting recycled waste plastic flakes to safe gamma radiation doses before grinding them into a soft powder. Additionally, their findings demonstrated that using this practical idea would be environmentally beneficial due to the fact that manufacturing concrete is responsible for 4.5% of global carbon dioxide emissions, Schaefer et al. [71]; Gregorova and Unčík [72]; Morsy and Jailany [73]; Li and Chen [74]; Maghfouri et al. [75].

To locate the effects of recycled WP as a partial replacement on concrete properties, Almeshal et al. [76] managed a study employing some replacement ratios of recycled WP in concrete. According to those scientists, plastic has a significant adverse environmental impact that requires to be treated and reduced. Polyethylene terephthalate was utilized in their work to substitute a portion of the sand in the concrete. Their experimental research on the new concrete mix's mechanical and physical features relied on six polyethylene terephthalate-filled concrete samples, corresponding to replacement proportions of 0%, 10%, 20%, 30%, 40%, and 50%. The concrete specimens' compressive strength, tensile strength, workability, flexural strength, fire resistance, and pulse velocity were estimated to determine the new concrete behavior. Their empirical outcomes revealed that while other mechanical and physical qualities were enhanced, the unit weight was decreased. These outputs suggested that employing recovered WP could improve the characteristics of concrete instead of excessive sand quantity.

Ahmad et al. [77] carried out a study assessing the critical influences of recycled WP from electronics on the performance and characteristics of concrete when certain proportions of recycled WPs are harnessed. To reach their goal, they prepared a group of six concrete specimens. They replaced some of the concrete's content with percentages of natural coarse aggregate (10%, 20%, 30%, 40%, and 50%) and coarse plastic aggregate made from electronic waste, which served as partial replacements for natural coarse aggregate. By measuring the alternate wetting and drying rate, ultrasonic pulse speed, abrasion resistance, sorptivity coefficient, compressive strength, flexural strength, splitting tensile strength, dry density, fresh density, and workability, they verified the effectiveness and influences of recycled WP in concrete. Depending on their work, the strength of the material recorded a decline between 9.9% to 52.7% for compressive strength, 7.8% to 47.5% for splitting tensile strength, and 11.4% to 39.4% for flexural strength, respectively. On the other hand, the findings confirmed that adding coarse plastic aggregate (between 10% and 50% of replacement) elevated the concrete's durability and workability.

Al-Tayeb et al. [78] guided an analysis classifying valuable gains of WP's implementation in concrete on its mechanical performance. The scholars relied on a partial replacement of sand with particular ratios of WP. They performed an experimental analysis through which sand replacement percentages of 0%, 5%, 10%, and 20% were considered for four specimens of concrete mix. The mechanical characteristics of new concrete mixes were studied by estimating the failure in three beams with dimensions of 400 mm in length, 100 mm in breadth, and 50 mm in depth. For 90 days, those three beams were subjected to a 30 N strain load. Three additional beams were evaluated using a static loading of the same size and duration. Their outcomes showed that the bending in these beams had a minimum value when 20% of the sand was replaced with WP. As a result, concrete mixes with higher proportions of WP could have greater compressive and tensile strengths and might be able to absorb more energy.

3.1 Influences of recycled Nanoplastics on concrete's workability

As mentioned previously, integrating WP into concrete would achieve some considerable amendments in its mechanical properties, notably its workability.

Table 3. Findings related to the workability property considered by various researchers via WP/NP involvement in concrete

No.	Author(s)	Effect of WPs/ NPs Integration in Concrete on Workability
1	Park and Kim [83]	Using WP particles would enhance fresh concrete properties.
2	Boucedra et al. [84]	Workability and fresh properties can be promoted after WP is integrated into concrete.
3	Ahmad et al. [85]	Fresh characteristics of the concrete mix were elaborated when specific ratios of WPs were used.
4	Fonseca et al. [86]	WP employment contributed to a relatively remarkable augmentation of workability and fresh properties of concrete.
5	Rohden et al. [87]	Workability was improved after WP replaced some portions of particular concrete components.
6	Farina et al. [88]	Fresh properties were boosted when the concrete mix was amended and supported by virtue of WP particles.

Workability is a vital characteristic of concrete material as it is associated with the flexibility and possibility of the fresh concrete mix to be mixed, positioned, consolidated, and finished under lower leakage or degradation rates under homogeneity circumstances, Kharun and Svintsov [79]; Shi et al. [80]; Carvalho and Motta [81]; Zi Mun et al. [82].

Scholars and civil engineers have addressed and examined the addition of NPs and WPs into the concrete mix. They found some positive modifications and valuable amendments that could be attained after some ratios of waste plastics are integrated into concrete. Table 3 represents some findings related to the workability property investigated by various authors.

Concurrently, Yin et al. [89] guided analytical research exploring the major contributions of WP fiber on concrete's workability when integrated under particular and careful proportions. Similarly, Mazaheripour et al. [90] assessed the workability features in new concrete mixes containing specific rates of WP fibers. Meantime, Hasan et al. [91] executed equal analytical work exploring workability characteristics in the new concrete mix. Those three publications confirmed that utilizing 10%, 20%, and 30% of WP fiber fractions could lead to minimal levels of workability due to the presence of a complicated network in the new concrete structure, as expressed in Figure 6. In turn, this complex structure could lower slump (a fresh concrete property), contributing to minimized workability.

Figure 7 illustrates a comparative analysis of the stress-strain ($\sigma - \varepsilon$) curve pertaining to concrete mixes; (a) with and (b) with no plastic fibers.

Figure 6. New complex synthesis of concrete with WP fibers [92]

Likewise, Poonyakan et al. [92]; Mohamed and Djamila [93] validated decreasing kind of workability in the new concrete mix when WP fibers were integrated into concrete. The reason for this observation was due to the significant degree of porosity that was risen with larger WP fiber volume fractions.

Figure 8 describes the subsidence rates (in mm) connected with different portions of plastic fibers in the concrete mix.

It can be inferred from Figure 8 that after considering the integration of High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polyethylene Terephthalate (PET), and Polypropylene (PP), it is noted that the subsidence scales dropped down compared with the reference/control specimen of concrete, indicating lower workability of new concrete mixes.

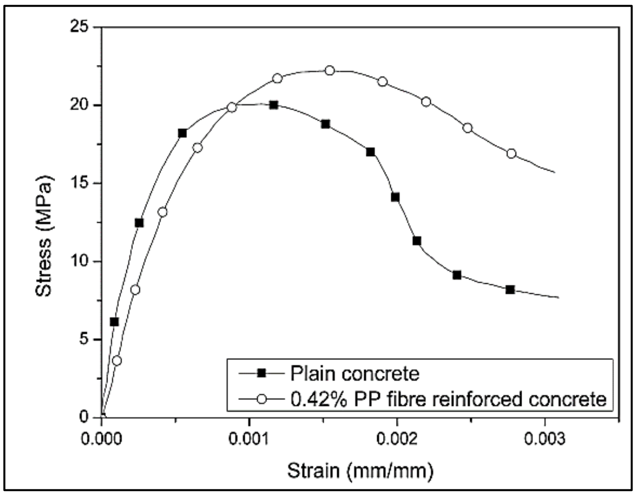

Figure 7. Stress-strain curves linked to concrete mixes; (a) with and (b) with no plastic fibers [89]

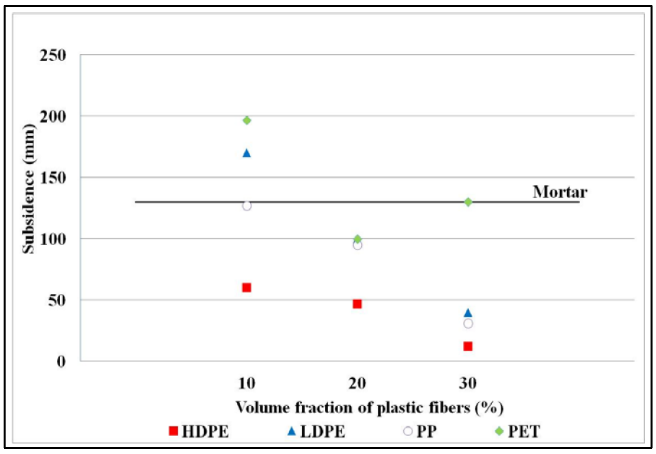

Figure 8. The subsidence rates (in mm) related to different portions of plastic fibers in the concrete mix

3.2 Effects of recycled Nanoplastics on durability

Table 4. Durability enhancements using the WP in concrete

Author(s) and Year	Types of WP Considered	Effects on Durability after WP Particles were Integrated into Concrete
Yalley [66]	NPs	Elaborated
Lamba et al. [28]	PP, PET, HDPE, LDPE, and Polyvinyl Chloride (PVC)	Enhanced
Gesoglu et al. [94]	PVC	Elaborated
Jassim [95]	Polyethylene (PE)	Enhanced
Manjunatha et al. [96]	PVC	Elaborated
Manjunatha et al. [97]	PVC	Enhanced
Manjunatha et al. [98]	PVC	Elaborated
Najaf and Abbasi [99]	Poweders of PET, PE, PP, Polycarbonate (PC), and/ or PVC	Enhanced
Poonyakan et al. [92]	PP, PET, HDPE, LDPE, and PVC	Enhanced
Ferrotto et al. [100]	PET, PP, and PVC	Elaborated
Waysal et al. [101]	PET	Elaborated

Different authors investigated the impact of adding NP/WP into concrete on its durability. Table 4 represents the results of durability enhancement using WP in concrete.

It is worth mentioning that the durability property of concrete is linked to the concrete ability to resist weathering circumstances and severe environmental conditions, reflected in abrasion, wear, chemical attack, and other challenging conditions to provide optimum concrete characteristics without causing degradation or deterioration in the concrete's mechanical properties.

4. EFFECTS OF RECYCLED NANOPLASTICS ON CONCRETE'S THERMAL PROPERTIES

Besides the enhancements to concrete's mechanical properties, using WPs would achieve significant energy-savings, boost economic feasibility, and help make buildings more sustainable by employing some proportions of recycled WP. As various scholars noted, the reason is related to the plastic nature of very low thermal conductivity compared with sand and cement. This critical property makes concrete more effective in terms of thermal insulation. Hence, cooling and heating demands in summer and winter can be remarkably mitigated, respectively. Demirboga and Kan [102] conducted an analytical work estimating the thermal conductivity of concrete after WPs were integrated into the new concrete mix. Similarly, Khalil and Mahdi [103] examined the thermal performance of concrete when some portion of WPs were addressed. Meantime, Poonyakan et al. [92] explored critical relevances in the thermal effectiveness of concrete when specific percentages of WP are integrated into new concrete mixes. Those three papers affirmed that WP utilization in the concrete could remarkably alleviate thermal conductivity, helping make concrete more thermally stable and effective insulators. Additionally, they found that more thermal reliability and efficient insulation aspects could be fulfilled by engaging WPs in concrete.

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This research was guided to identify the major significance and vital advantages of integrating NPs into concrete in terms of mechanical and thermal properties. Also, this study is led to highlight some environmental benefits of using NPs in concrete. Based on the comprehensive review considered in this work, the research findings can be summarized in the following points:

(1) The use of recycled NPs/ recycled WPs in concrete could achieve some positive environmental impacts reflected in the reduction of tiny WPs that may cause air and water pollution.

(2) Employing recycled NPs/ recycled WPs helps reduce the cost of concrete and makes it more sustainable by making some replacements for cement or sand using NPs.

(3) Replacing some ratios of sand or cement in concrete with recycled NPs/ recycled WPs (partially or wholly) would contribute to different beneficial enhancements in the thermal properties (like increasing concrete's thermal resistance) and enhancing its mechanical characteristics, such as shrinkage, splitting tensile strength, compressive strength, shear resistance, and flexural strength).

(4) There is a considerable lack of research publications that address the critical role of NPs in enhancing different concrete properties. Most of the research articles discussed and focused on the beneficial impacts of plastics (and, in a few publications: microplastics). But the global literature remarkably lacks similar investigations of concrete's mechanical and thermal properties when the cement is replaced with recycled NPs effects.

(5) There is a need for further studies that take into account the calculations and assessments of carbon emissions and environmental impact indices after obtaining the new concrete mix that employs NPs, replacing entirely or partially cement or sand.

(6) There is a requirement to increase the number of studies to improve the thermal properties of concrete. Diverse articles explored the influences of using NPs/ recycled WPs/ on concrete's mechanical properties. But a small number of articles evaluated its thermal properties.

5.2 Future work

Depending on the research outcomes obtained from this review work, it is strongly recommended to follow more critical research steps and analytical procedures that could bridge the research gap of NP influences on concrete's mechanical, thermal, and ecological features. Those vital futuristic suggestions are summarized in the following points:

(1) To lead plenty of experimental investigations that are currently rare, helping validate the influences of NPs on various concrete properties,

(2) To administer multiple numerical experimental processes via which simulations and mathematical modeling can be implemented to address the influences of NPs.

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