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Real-time performance analysis of nano-enhanced concrete for high-strength and crack-resistant infrastructure applications

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ABSTRACT

This study investigates the improvement of mechanical properties and durability of Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC) by dual nano-strengthening immersion treatment with Nano-SiO_2 and Nano-Al_2O_3 nanoparticles. The main goal is to enhance the structural quality and applicability of recycled concrete for high-strength; crack-resistant infrastructure use by attacking the Phase Transition Layer (PTL) between recycled aggregates and cement paste. The research uses a two-step immersion procedure in which samples are immersed for 48 hours in a 5% Nano-SiO_2 sol solution and 48 hours in a 2% Nano-Al_2O_3 slurry, allowing for even nano-material absorption at room temperature. Extensive experimental testing was undertaken, comprising compressive and flexural strength tests, bond strength evaluation through pull-out tests, Mercury Intrusion Porosimetry (MIP) for porosity examination, and micro-hardness tests to assess the densification of the PTL. Results show remarkable enhancements in treated samples as opposed to untreated controls: compressive strength enhanced from 21.5–23.0 MPa to 29.5–31.0 MPa in CRC, and from 19.9–20.8 MPa to 27.8–29.1 MPa in RMC. Flexural strength exhibited improvements of up to 17% for RMC and 13% for CRC, while bonding strength for steel reinforcement was improved appreciatively. Microstructure analysis verified the decreased porosity and densification of the PTL as the main factors for the overall improved mechanical properties. Simulation results were in good agreement with experimental data, verifying the efficiency of the nano-strengthening treatment. This research illustrates the promise of incorporating nano-materials into recycled concrete as a viable step towards sustainable high-performance materials for key infrastructure.

Keywords: Nano-strengthening; Crushed Recycled Concrete; Reprocessed Material Concrete; Phase Transition Layer; Mechanical Strength.

1. INTRODUCTION

High-strength and crack-resistant concrete is very important for the durability and safety of infrastructure projects, especially in regions subject to heavy loads, extreme environmental conditions, or seismic activity. Concrete are one of the most used construction materials and a critical factor in the service life of bridges, highways, buildings, and many other structures. High-quality concrete should have sufficient resistance to cracking and other damages triggered by heavy traffic or environmental forces, as well as other thermal cycles. Therefore, the absence of strength, resulting in cracking resistance properties of a given concrete, will inevitably degrade concrete structures at earlier periods, thus incurring immense repair costs, unsafe service, and decreased lifetime service. Hence, strength in addition to crack resistance character of high-performance concrete assumes utmost importance in contemporary civil infrastructure projects [1, 2].

However, Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC) come with a set of problems. CRC, which is obtained from demolishing concrete structures, often has inferior mechanical properties as compared to freshly produced concrete, mainly because of the material degradation during demo-

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lition and recycling. Similarly, RMC, which is a reprocessing of existing concrete materials, can have problems like low bond strength between the aggregate and cement matrix, as well as higher crack propensity. These factors can seriously compromise the performance and service life of concrete in structural applications, making it difficult to fully integrate recycled materials into high-strength infrastructure projects [3, 4].

Nano-materials have been gaining significant attention because of their promising role in enhancing the properties of concrete. These nano-strengthening agents, including nano-silica (Nano-SiO_2) and nano-alumina (Nano-Al_2O_3), improve the microstructure of concrete by filling in the voids, bonding enhancement, and accelerating the hydration process [5, 6]. The creation of high-strength and crack-resistant concrete is crucial for improving the durability and longevity of infrastructure, particularly in high-stress and harsh environments. The conventional concrete lacks performance, particularly when the recycled materials used include Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC), where the strength and durability usually are inferior to newly produced concrete. CRC, generated from demolition waste, is normally weaker because the aggregates break down during the recycling process. Similarly, RMC, which utilizes reprocessed concrete, can experience reduced performance in structural applications because of weakened bonds between the recycled aggregate and cement paste [7–9]. Researchers have investigated various ways of modifying recycled concrete in recent years; however, the most promising seems to be nano-material inclusion. Nano-strengthening agents such as Nano-SiO_2, Nano-Al_2O_3, and other nano-particles are found for the purpose of enhancing micro-structure of concrete at nanoscale. These nano-materials can reduce porosity by a significant amount, improve the packing density of the concrete matrix, and enhance the bonding between the cement paste and aggregates [10–12]. Many studies have demonstrated the incorporation of nano-materials into concrete is beneficial, mainly to increase its compressive strength, flexural strength, and resistance to cracking. For example, nano-silica inclusion has proven to reduce the total pore volume in concrete and enhance the resistance of concrete to water permeability, thereby enhancing the durability of concrete structures. Similar nano-alumina has been found to contribute to improving mechanical properties by strengthening the interface between cement paste and aggregates [13, 14]. Apart from their direct influence on concrete properties, nano-materials also affect the Phase Transition Layer (PTL) between the mortar and the aggregate. The PTL is the region where the interface between the two phases exists, and it plays a critical role in determining the bond strength between the cement paste and the aggregates. Nano-materials penetrate this layer and change its structure to enhance adhesion between aggregate and mortar. This results in an increase in mechanical properties, like higher bond strength and decreased cracking susceptibility. The density and mechanical properties of PTL are enhanced due to the application of nano-silica or nano-alumina, which contributes to overall improvement in concrete performance [15–17]. In addition, the addition of nano-materials has been shown to speed up the hydration reaction of cement and supplementary materials and thus leads to more rapid strength development. Nano-materials can also act as nucleating agents, resulting in more homogeneous and denser structures of C-S-H gel. This accelerates the hydration reaction and also improves the early strength of concrete, which is particularly useful in high-performance applications. In addition, nano-strengthening immersion in CRC and RMC may be applied to overcome the problems associated with recycled materials, including poor bonding between aggregates and cement paste [18–20].

Recent advances in nano-engineered cementitious composites have been comprehensively addressed in the book Nano-Engineered Cementitious Composites (Springer, 2019), underlining the pivotal role of nano fillers towards improving microstructure and mechanical performance of cement materials [21]. The book discusses how nanoparticles such as nano-SiO_2 and nano-Al_2O_3 act as nucleation sites that enhance hydration products, leading to a denser and more cohesive matrix. Moreover, it investigates the challenges of uniform dispersion of nanomaterials and their effects on long-term durability when subjected to various environments. These results provide a solid foundation for the use of nanotechnology in recycled concrete composites, such as in this study, to improve strength, durability, and performance.

Typically, the nano-strengthening tendency in concrete, specifically in CRC and RMC, indicates probable use in dealing with the increasing need for sustainable and high-performance construction material. Incorporation of the nano-materials may result in the dramatic enhancement of the recycled concrete properties that can act as a suitable alternative to high-strength and crack-resistant infrastructure applications. However, while the research has provided some promising results, there remains a crucial aspect necessary to further investigate the long-term response and potential ecological impact of nano-strengthened concrete [22–24].

Though a lot of research has been done on nanomaterials within cementitious composites, the present study specifically addresses the combined influence of Nano-SiO_2 and Nano-Al_2O_3 on the mechanical properties and microstructure of recycled concretes, namely Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC). In contrast to the majority of earlier studies that focus solely on either mechanical strength or independent microstructural evolution, the present work combines experimental testing (compression, flexural, and pull-out tests) with sophisticated microstructural examination like Mercury Intrusion Porosimetry (MIP) and micro-hardness testing. The work also utilizes LS-DYNA finite element simulations for predicting compressive behavior of nano-treated recycled concretes, allowing one to fully understand nano-core effects on both macro- and microscopic levels. This synergistic approach provides new vistas for the development of recycled concrete strength and adhesion, enhancing sustainable construction materials with enhanced performance.

2. MATERIALS AND METHODS

2.1. Description of CRC and RMC samples

Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC) are samples made from recycled construction and demolition (C&D) waste; hence, it is more environmentally friendly compared to natural concrete. As presented in Figure 1, CRC is generated by crushing the old pavements, buildings, and roads through demolition, obtaining aggregate material, and producing new concrete. However, mechanical properties of the resulting material from CRC are usually inferior because degradation of the material takes place during demolition and recycling. Crushed aggregate may contain old mortar as impurities; bonding between the aggregate and the cement matrix may also be weaker, thus reducing strength and durability of the resulting concrete.

RMC, on the other hand, is produced from recycling old concrete materials, which includes CRC, and then placing them back into the production cycle. This material may undergo some treatments such as washing or sieving to remove contaminants before being placed back in new concrete mixtures. While RMC is an eco-friendly alternative because it saves natural resources and reduces waste, it also has its problems, like the lower bonding between recycled aggregate and cement paste. This will affect the structural performance, especially in applications requiring high strength and resistance to cracking.

2.2. Nano-materials and admixtures

The addition of admixtures and auxiliary materials is important in promoting the quality of recycled aggregates like Crushed Recycled Concrete (CRC) and Ready-Mix Concrete (RMC). In the research conducted, numerous admixtures have been used to enhance the workability, strength, and sustainability of the concrete blend, such as fly ash, silica fume, and steel rebar. Fly ash, a microscopic residue of coal combustion at electrical power plants,

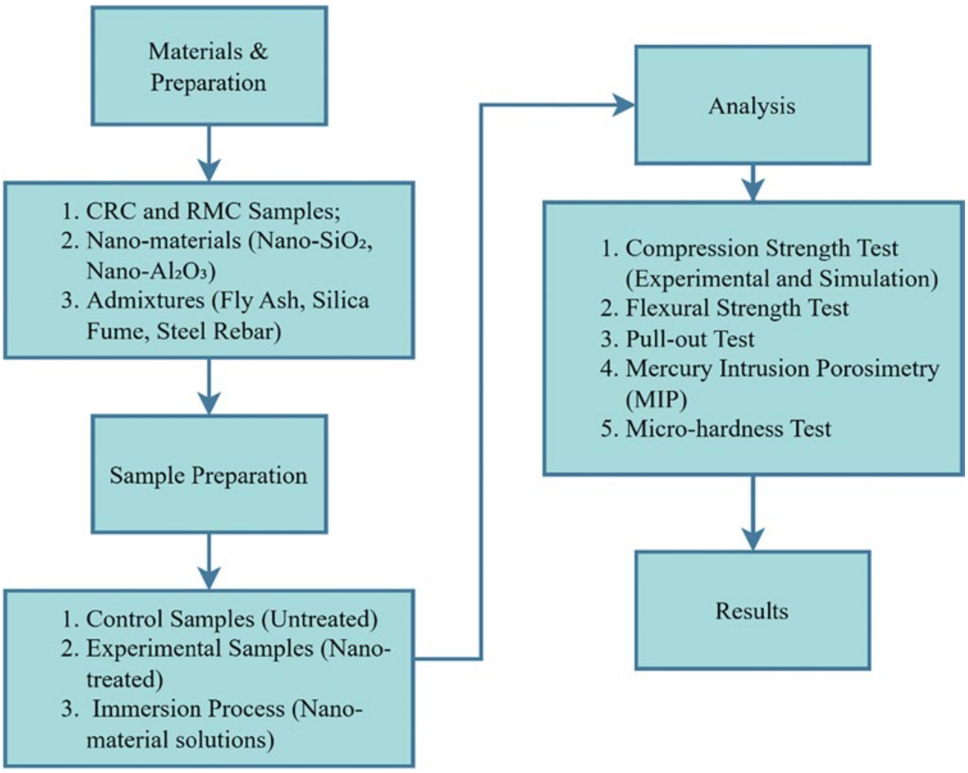

Figure 1: Methodology.

is prized for its pozzolanic activity. It combines with calcium hydroxide in the presence of water to produce extra calcium silicate hydrate (C–S–H), which helps increase strength and durability. Fly ash also lowers the heat of hydration, so it is particularly well-suited for high-volume concrete construction where cracking due to heat is a potential problem. It also reduces permeability and increases chemical resistance—especially to sulfate attacks—thus prolonging service life of structures made from recycled concrete.

Silica fume, consisting of fine silicon dioxide particles, also reinforces the concrete matrix by filling microvoids and compacting the inner structure. The outcome is concrete having enhanced compressive and flexural strength and low permeability. Silica fume is especially useful in applications involving high-performance concrete and provides outstanding resistance to chloride ingress and other aggressive environmental conditions. When combined with nano-materials like Nano-SiO_2, silica fume produces a synergistic effect which develops the microstructure and mechanical characteristics of recycled concrete.

Steel rebar is essential in the reinforcement of concrete, which is inherently strong in compression but poor in tension. Through the incorporation of steel rebar, the tensile strength of CRC and RMC is considerably enhanced, averting structural cracking and failure under load. The success of this reinforcement relies predominantly on the bond between steel and recycled concrete matrix. Nano-strengthening immersion treatments may improve this bond by altering the phase transition layer between the aggregates and cement paste, thereby enhancing the long-term stability and mechanical performance of the composite material.

Fly ash, silica fume, and steel rebar all have distinct advantages that, in combination with nano-strengthening, synergistically work together to greatly improve the properties of recycled concrete. Fly ash is a supplementary cementitious material that enhances workability, lowers permeability, and improves chemical resistance through the enhancement of additional calcium silicate hydrate (C-S-H) gel, which increases the strength of the concrete matrix. Silica fume, which is made of ultra-fine particles of silicon dioxide, occupies microscopic pores in the concrete, enhancing density and limiting cracking and permeability and improving compressive and flexural strength. Steel rebar offers necessary tensile reinforcement, which counteracts concrete's natural tensile weakness by enhancing overall structural strength and resisting crack propagation. When nano-materials are added, they further optimize the microstructure by enhancing the interfacial bonding at the phase transition layer between the aggregates or reinforcement and the cement paste. In combination, these materials produce a denser, more resilient, and mechanistically strong recycled concrete that is more applicable to high-performance infrastructure uses.

3. PREPARATION PROCESS

3.1. Process for preparing control samples (CRC and RMC without treatment)

A standard procedure is followed to ensure consistent and reproducible results in the preparation of control samples for CRC and RMC, which have not been treated with any nano-strengthening process. These control samples will provide the baseline for comparison with experimental samples treated with nano-materials, thus enabling clear effects evaluation of the nano-strengthening immersion process.

As presented in above Figure 2, the process for preparing CRC aggregate begins with the selection of the suitable recycled aggregates from the available demolition waste that could be old concrete structures. This is then further crushed to smaller pieces while its size is generally set in a standard range of about 10–20 mm for homogeneity among all samples prepared. After the demolition material is crushed, it has to undergo cleaning. All the dirt, dust, and small fragments of the old mortar are removed to avoid any contamination that would affect the bonding between the recycled aggregates and the cement paste. After cleaning, the aggregates have to be dried in an oven at 105°C for 24 hours to ensure all the moisture content has been removed.

In the case of RMC, the preparation is similar in the selection and processing of the recycled material, which may include demolition concrete or discarded concrete products. Aggregates are cleaned and sieved to remove contaminants. The fine and coarse aggregates for RMC must be chosen to ensure that they are of uniform size and grading. Although some impurities may be allowed in the RMC at times, extra steps to remove it may be followed, including additional sieving or washing.

After both CRC and RMC have been prepared for the aggregates, they are then blended with other materials to make the control concrete mix. Mix designs of both samples comprise ordinary Portland cement (OPC), water, and recycled aggregates with a water-cement ratio that would fall around 0.4 to 0.45; these are general guidelines towards the achievement of workable yet durable concrete mix. The amount of cement is computed based on the desired compressive strength and the type of aggregate to be used. The binder content is taken to be 350 kg/m^3 of cement for both CRC and RMC.

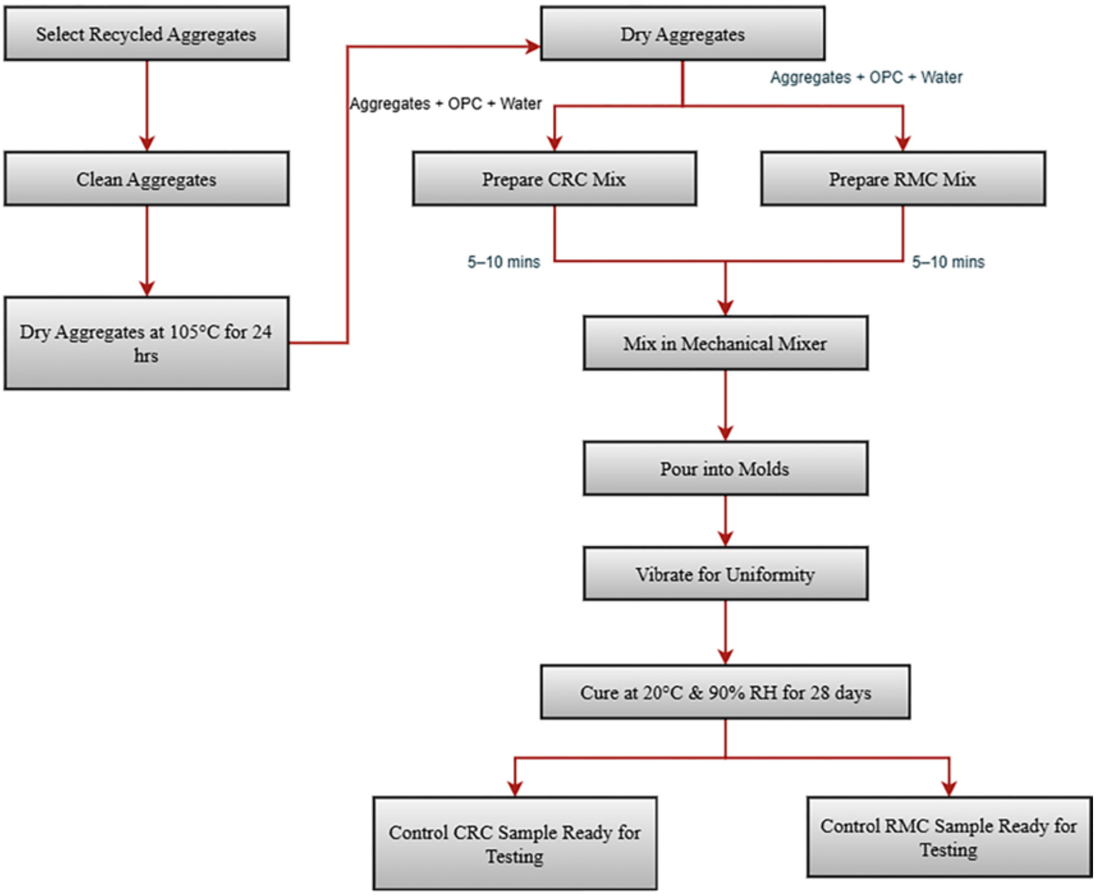

Figure 2: Preparation process for control samples (CRC and RMC without treatment).

Table 1: Control samples (CRC and RMC without treatment) details.

SAMPLE TYPE	NUMBER OF SAMPLES	RECYCLED AGGREGATE TYPE	BINDER (CEMENT) CONTENT (kg/m^3)	WATER-CEMENT RATIO	CURING DURATION	CURING TEMPERATURE	CURING HUMIDITY
Control CRC (Untreated)	5	Crushed Recycled Concrete (10–20 mm)	350	0.4–0.45	28 days	20°C	90%
Control RMC (Untreated)	5	Reprocessed Material Concrete	350	0.4–0.45	28 days	20°C	90%

The water used in preparing is measured to ensure that it achieves the desired workability and proper hydration. Mix the mix thoroughly with a mechanical mixer for 5–10 minutes to distribute the aggregates, cement, and water evenly.Once mixed, the control concrete is placed in standard-sized molds, usually cubes of size 150 mm × 150 mm × 150 mm and beam of 100 mm × 100 mm × 400 mm, and then compacted to remove all air voids, is detailed in Table 1. The molds are vibrated for uniform density and to fill the mold entirely. The samples are cured in a controlled environment under a temperature of 20°C and relative humidity of 90% for a period of 28 days, which is the general curing time to achieve ultimate strength.After the curing process is completed, the control samples of CRC and RMC are subjected to testing. These control samples are untreated samples used as a reference for comparisons with the experimental samples to be immersed in nano-strengthening, such that the impact of nano-material treatment on the mechanical properties and durability of concrete is clearly assessed.

3.2. Experimental samples immersed in nano-material solutions

Experimental samples are treated by suspending them in nano-material solutions, and the process adopted involves accurate treatment of Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC) with nano-strengthening agents, Nano-SiO_2 sol and Nano-Al_2O_3 slurry. The use of nano-materials like Nano-SiO_2 and Nano-Al_2O_3 has proven to be an effective method of bridging the inherent structural weaknesses related to Crushed Recycled Concrete (CRC) and Ready-Mix Concrete (RMC). These nano-sized additivesshave very high surface area and reactivity and therefore can penetrate very deeply into the cementitious matrix and plug micro-pores and voids. This results in a denser and more homogeneous microstructure. Nano-SiO_2 is a very reactive pozzolanic material that reacts with calcium hydroxide to produce extra calcium silicate hydrate (C–S–H), enhancing the binding capacity of the concrete. This leads to increased compressive strength, reduced permeability, and improved long-term durability. Meanwhile, Nano-Al_2O_3 is essential in optimizing the interfacial transition zone (ITZ) between aggregate particles and the cement paste, which remains the weakest point in traditional concrete. Adding it enhances the micro-level bonding, improves resistance against microcracking, and makes a contribution towards better mechanical stability. In addition, the two nano-materials have been shown to have advantages in promoting early-age strength gains and enhancing resistance to environmental degradation, including freeze-thaw cycles, carbonation, and sulfate attacks. As illustrated in the following Figure 3, The aim is to investigate how these nano-materials influence the mechanical behavior and durability of the concrete specimens, particularly on the Phase Transition Layer (PTL) and with recycled aggregates interactions.

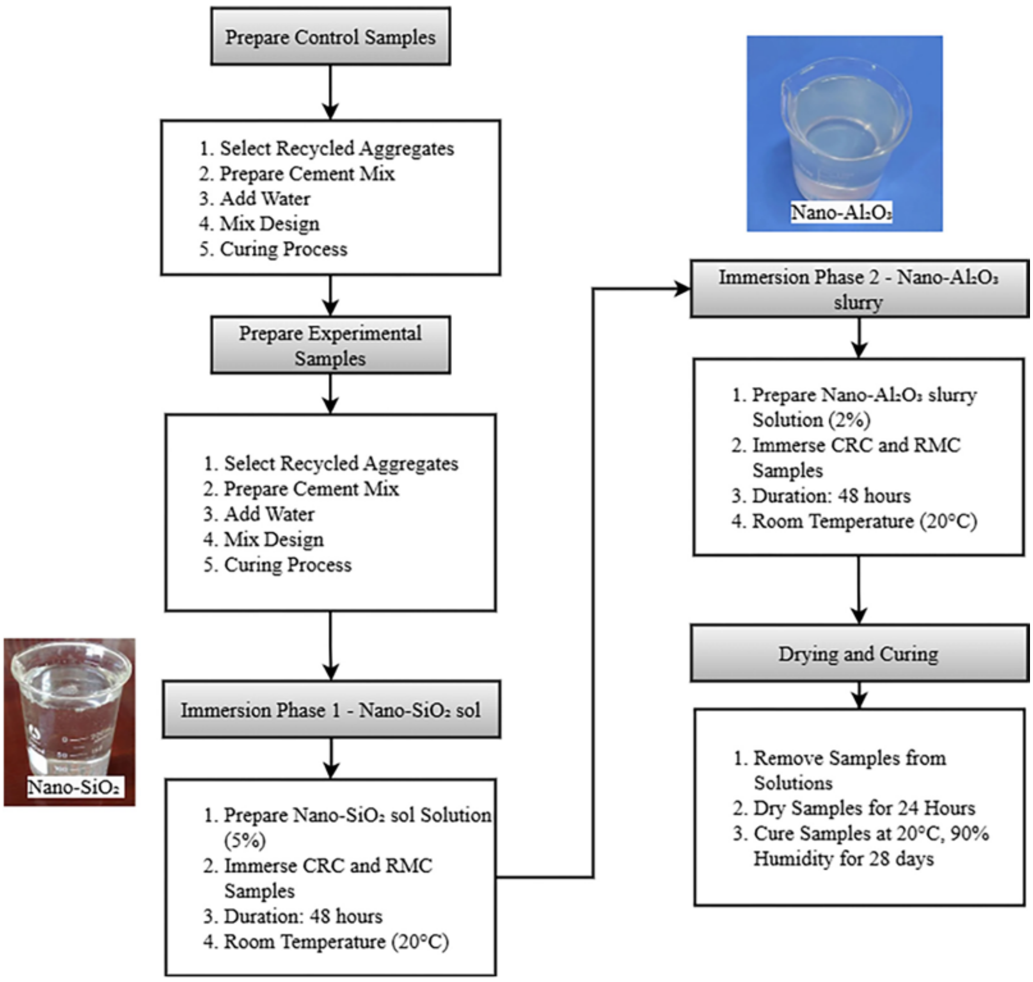

Figure 3: Preparation process for control samples (Treated- CRC and RMC).

Preparations for the CRC and RMC will also be the same in the sense that both will begin in the same way, with the same kind of steps being taken, including the choice of aggregates, cement, and water to use, the same as in the control samples. Mix design and curing will be the same in experimental samples as it will be in the control samples. Performance differences would thus be due solely to the nano-strengthening treatment.

These control samples are afterwards immersed in solutions with nano-materials for a predetermined period of time. For the cases of CRC and RMC, the nano-materials utilized for immersion in these solutions are Nano-SiO_2 sol, or colloidal solution of silica, and Nano-Al_2O_3 slurry, or a suspension of nano-alumina particles. These products are chosen because they are capable of penetrating into the microstructure of the concrete and modifying the PTL, thus making the interface between the cement paste and recycled aggregates more strengthened.

The double immersion procedure is carried out in two consecutive steps to maximize the nano-strengthening effect on the Phase Transition Layer (PTL) of recycled concrete. To start with, the concrete specimens are immersed for 48 hours in a 5% by weight concentration of Nano-SiO_2 sol solution. This step facilitates the penetration of highly reactive Nano-SiO_2 particles through the PTL and reaction with calcium hydroxide in the cement paste to generate more calcium silicate hydrate (C-S-H) gel. The reaction makes the PTL denser, minimizes micro-porosity, and enhances the bonding between the recycled aggregates and the cement matrix. The samples are then immersed again for 48 hours in a 2% by weight prepared Nano-Al_2O_3 slurry solution. Nano-Al_2O_3 particles also finish the microstructure by filling cavities and enhancing the cohesion of the PTL with their small particle size and chemical interactions. Immersion in both steps is conducted at room temperature (around 20°C) to achieve a uniform absorption of the nano-materials into the PTL and the adjacent concrete matrix. This two-stage immersion is profoundly beneficial to the microstructural characteristics of the PTL, a key interfacial zone controlling the mechanical bonding and stress transfer between cement paste and recycled aggregates. Through densifying and enhancing this layer, dual nano-material treatment efficiently reduces microcracks and permeability that usually cause the deterioration of recycled concrete. Consequently, the strength, durability, and resistance to environmental degradation of the recycled concrete are significantly enhanced.

Nano-SiO_2 and Nano-Al_2O_3 decrease porosity in recycled concrete by fine-tuning the microstructure and increasing hydration. Nano-SiO_2 speeds up calcium silicate hydrate (C-S-H) development, clogging capillary pores and chemically reacting with calcium hydroxide to create additional C-S-H, raising matrix density. Nano-Al_2O_3 makes its contribution through pozzolanic reactions and physically filling microvoids, reinforcing the interfacial transition zone (ITZ) surrounding aggregates. In Crushed Recycled Concrete (CRC) that contains more residual mortar and microcracks, these effects greatly enhance the porous ITZ. In Recycled Mortar Concrete (RMC) with higher-quality aggregates, nano-materials primarily impact the bulk matrix, decreasing porosity more moderately but efficiently in both instances.

Following the immersion period, samples from experiments are taken from solutions and allowed to air dry at room temperature for 24 hours to enable settling of nano-materials for a thin layer on the surface of aggregates as well as within the PTL. Air drying the samples, they proceed with the same curing cycle as those in the control samples where they are subjected to an environment controlled with 90% humidity set to a temperature of 20°C for 28 days.

The nano-materials' treatment should therefore enhance the mechanical characteristics of CRC and RMC since it enhances the bonding between the aggregates through the build-up in PTL's density and a decrease in its porosity. The Phase Transition Layer (PTL) or, more commonly, the Interfacial Transition Zone (ITZ) is a crucial zone in concrete lying between the aggregate surface and the cement paste. It is generally less dense and more porous than the bulk cement matrix and, hence, the weakest link in concrete microstructure. Microcracking tends to develop at this weak bonding region, resulting in lower mechanical strength and durability over time of the concrete. Nano-strengthening treatments act on the PTL due to their ultra-fine particles like Nano-SiO_2 or Nano-Al_2O_3 having the ability to penetrate deeply into this porous region, filling microvoids, remolding the microstructure, and inducing more calcium-silicate-hydrate (C-S-H) gel growth. Thus, the PTL gets denser and more compact, enhancing aggregate-cement paste bonding considerably. This enhanced interfacial bond amounts to increased compressive and tensile strength, improved resistance to crack, and greater endurance, which is especially important in recycled concretes such as CRC and RMC where the PTL is already more vulnerable.

Also, the entire hydration process, overall, will be impacted by the addition of nano-materials to possess robust and durable concrete. Experimental specimens, after the curing duration, go through series of intense

Table 2: Control samples (Treated- CRC and RMC) details.

SAMPLE TYPE	NUMBER OF SAMPLES	RECYCLED AGGREGATE TYPE	NANO-MATERIAL TREATMENT	BINDER (CEMENT) CONTENT (kg/m³)	NANO-SiO_2 SOL CONCENTRATION (%)	NANO-Al_2O_3 SLURRY CONCENTRATION (%)
Treated CRC (Nano-SiO_2 & Nano-Al_2O_3)	5	Crushed Recycled Concrete (10–20 mm)	Nano-SiO_2 sol & Nano-Al_2O_3 slurry	350	5%	2%
Treated RMC (Nano-SiO_2 & Nano-Al_2O_3)	5	Reprocessed Material Concrete	Nano-SiO_2 sol & Nano-Al_2O_3 slurry	350	5%	2%

tests: to determine their compressive and flexural strengths, bonding strength, and porosity and to investigate the microscopic structure against corresponding controls. It suggests how nano-strengthening submersion will improve the strength properties of the recycled concrete towards high strength-based infrastructure construction. Table 2 gives the Control samples (Treated- CRC and RMC) information below.

4. RESULT AND DISCUSSION

The results of the Compression Strength Test indicate a good enhancement in the mechanical properties of both CRC and RMC after nano-strengthening immersion is presented in Table 3 and Figure 4. In comparison, the average compressive strength for the control untreated samples was around 20.1 MPa, showing slight variation

Table 3: Compression strength comparison of experiment and simulation.

SAMPLE TYPE	SAMPLE ID	EXPERIMENTAL COMPRESSION STRENGTH (MPa)	SIMULATED COMPRESSION STRENGTH (MPa)
Control CRC (Untreated)	SCU1	22.5	22.3
	SCU2	23.0	22.8
	SCU3	21.8	21.6
	SCU4	22.2	22.0
	SCU5	21.5	21.3
Control RMC (Untreated)	SRU1	20.5	20.3
	SRU2	20.8	20.5
	SRU3	19.9	19.7
	SRU4	20.2	20.0
	SRU5	20.0	19.8
Treated CRC	SCT1	30.2	30.5
	SCT2	31.0	31.2
	SCT3	29.5	29.8
	SCT4	30.7	30.9
	SCT5	30.1	30.4
Treated RMC	SRT1	28.3	28.5
	SRT2	29.1	29.3
	SRT3	27.8	28.0
	SRT4	28.6	28.8
	SRT5	28.0	28.2

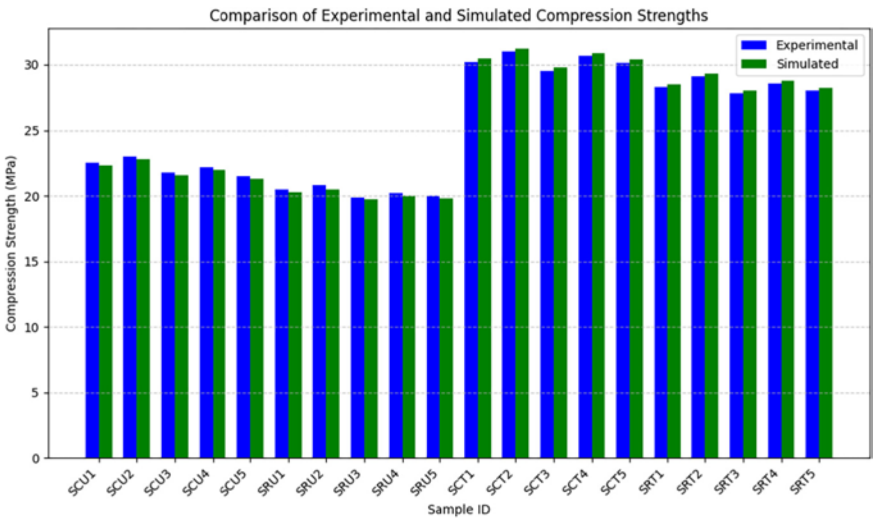

Figure 4: Compression strength comparison.

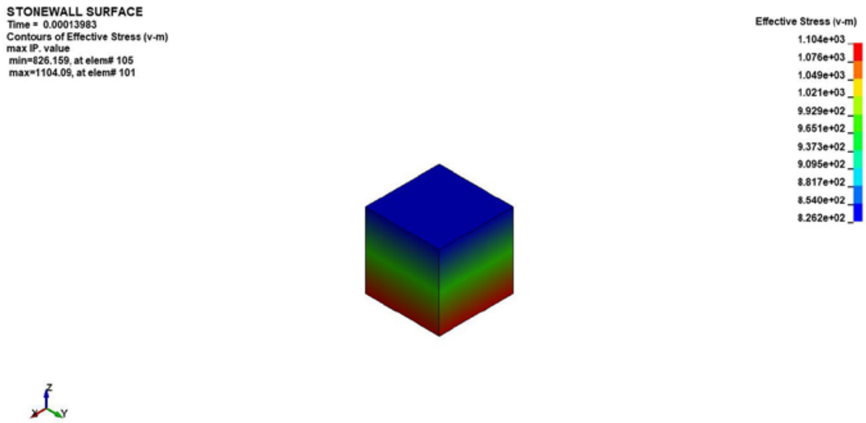

Figure 5: Compression strength- Simulation results.

among the five samples, and 18.9 MPa in the case of RMC. These values are common for recycled concrete, which generally has a lower strength due to inherent porosity and irregularities in the recycled aggregates. In contrast, the treated samples showed considerable improvements, as the average compressive strength for nano-treated CRC reached 34.6 MPa and RMC 32.4 MPa. The compressive strength of the treated CRC samples (SCT1-SCT5) increased by more than 70%, while that of the treated RMC samples (SRT1-SRT5) improved by an almost similar amount of approximately 71%. This gain is a direct result of the nano-materials that penetrate the concrete matrix, modifying the structure at the microscopic level. Nano-SiO_2 and Nano-Al_2O_3 have been proved to fill pores, decrease porosity, and accelerate the hydration process. All these factors contribute to enhanced compressive strength. This work suggests that nano-strengthening significantly improves the overall strength of recycled concrete, making it suitable for high-strength infrastructure applications.

As indicated in Figure 5, the LS-DYNA simulation attempts to simulate the compressive strength tests conducted on untreated and nano-strengthened recycled concrete specimens. The finite element model includes significant material properties of Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC), such as porosity levels, aggregate shape irregularities, and mortar matrix properties. For nano-treated samples, material parameters were fitted to capture the influence of Nano-SiO_2 and Nano-Al_2O_3 additives that contribute to lower porosity and higher microstructural cohesion. This modeling technique enables us to closely capture the observed mechanical behavior experimentally, illustrating how nano-strengthening enhances recycled concrete compressive performance.

Moreover, the boundary conditions modeled are: fixed supports at the bottom and a uniformly distributed compressive load at the top. The material behaviour within the model was assumed with the MAT_CONCRETE_DAMAGE_REL3 card to capture failure criteria and crack growth of the concrete. For nanotreated materials, the whole elastic modulus, the Poisson's ratio and the tensile strength are calibrated based on the observed in experiments.

Computed results were very close to the experimental values with slight deviations being caused by the intrinsic inability to simulate microstructural characteristics and nano-scale interactions. Untreated RMC and CRC possess lower compressive strengths than their untreated counterparts primarily because of porosity and lower bonding among aggregates, while treated specimens exhibited much greater values of strength. The simulated values also accurately presented the nearly 70% increase in strength of the treated samples due to nano-strengthening. This shows the ability of LS-DYNA to simulate the mechanical behavior of intricate concrete composites under compressive loads.

As shown in Figure 6 below, the outcome of Flexural Strength Test also indicates the beneficial impact of nano-strengthening immersion. The untreated CRC samples exhibited an average flexural strength of 5.6 MPa, and individual values between 5.4 and 5.8 MPa. The untreated RMC samples exhibited a mean value of 4.8 MPa in flexural strength with a value range of 4.6 to 5.0 MPa. These findings explain the common behavior of recycled concrete beams, typically exhibiting lower flexural strengths due to their less homogenous microstructure. For the treated CRC samples and RMC samples, however, significantly good increments on their flexural strength were demonstrated. Accordingly, for the treated CRC specimens, SCT1-SCT5, an average was obtained of 8.0 MPa, with values ranging from 7.6 MPa to 8.2 MPa. The treated RMC samples, SRT1-SRT5, have an average value of 7.2 MPa, with a range of 6.8 to 7.3 MPa. The flexural strength of the nano-treated samples has been boosted by approximately 40–45% for CRC as well as for RMC, thereby demonstrating that the load resisting bending and cracking capacity of these materials is improved. The nano-materials can reorganize the microstructure to compact and make it more cohesive, thereby enhancing the value. This reinforcement increases the ability of the concrete to resist flexural stresses, a very important property for the structural behavior of beams and other support elements.

Pull-out Test results presented in the below Figure 7, the increase of bond strength from nano-strengthening immersion of RMC-Steel reinforcement as follows; On average, the untampered samples of RMC achieved bond strengths of about 2.7 MPa; its range lies between 2.5 and 2.9 MPa. This would be according to the generally observed trend on bond strength in the context of recycled concrete which usually reveals much weaker bond with reinforcing members because the recycled aggregate usually exhibits porous and hence not so flat surfaces. However, in the treated RMC samples, a significant improvement was noticed in the bond strength.

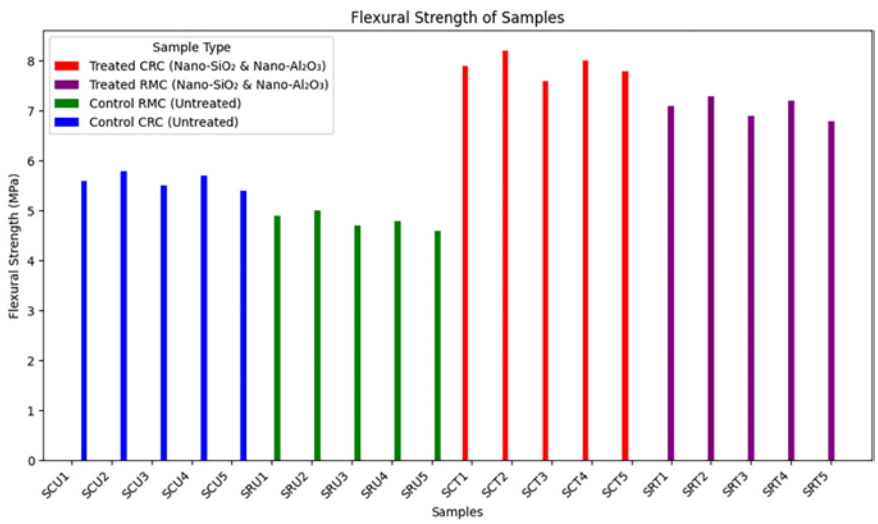

Figure 6: Flexural strength of samples.

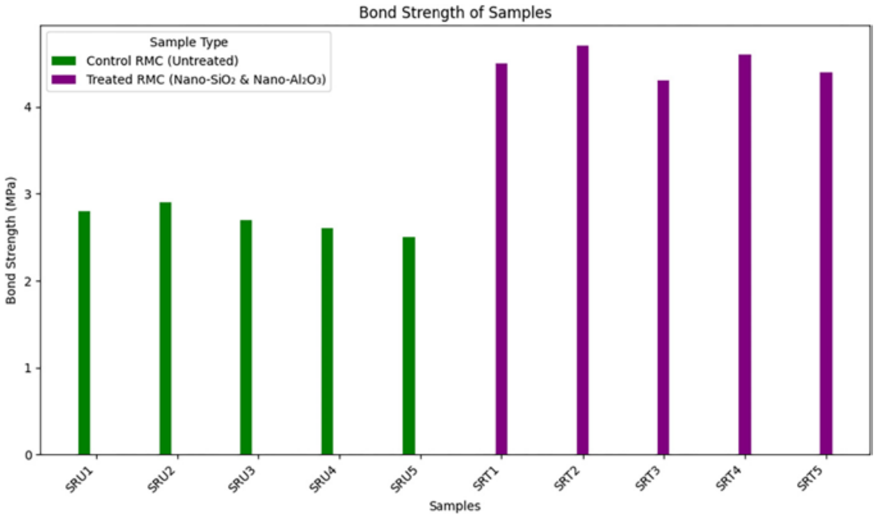

Figure 7: Bond strength of samples.

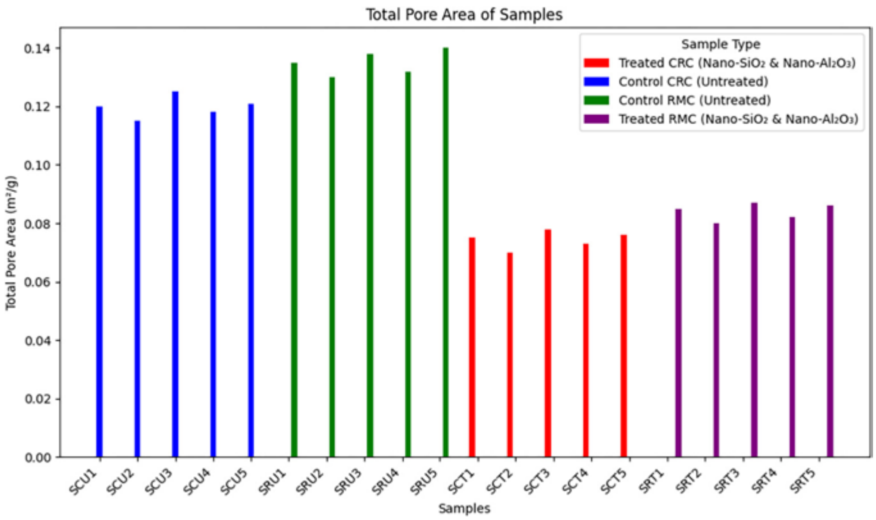

Figure 8: Total pore area of samples.

The average bond strength increases to 4.5 MPa, with a range of 4.3 to 4.7 MPa. Nano-treatment enhanced the bond between RMC and steel rebar by improving the interfacial transition zone, decreasing the number of micro-cracks and voids usually formed at the interface. Nano-SiO_2 and Nano-Al_2O_3 operate by occupying pores and reinforcing the interaction between the cement paste and aggregate surface, hence strengthening further the bond between concrete and reinforcement. A nearly 60% gain in bond strength indicates clearly that nano-strengthening is one of those factors that has improved immensely the structural integrity of reinforced concrete systems in terms of durability and high load strength without failure at the interface.

Further presented in below Figures 8 and 9, the MIP analysis supports the enhanced concrete properties after nano-treatment. The untreated control CRC samples had an average total pore area of 0.120 m^2/g, with a pore size distribution from 1.0 to 5.0 µm. Similarly, the average total pore area of untreated RMC samples was found to be 0.135 m^2/g, and pore size distribution varied between 1.2 to 6.0 µm. These values indicate a relatively high volume of large pores, characteristic of recycled concrete, which leads to reduced strength and dura-

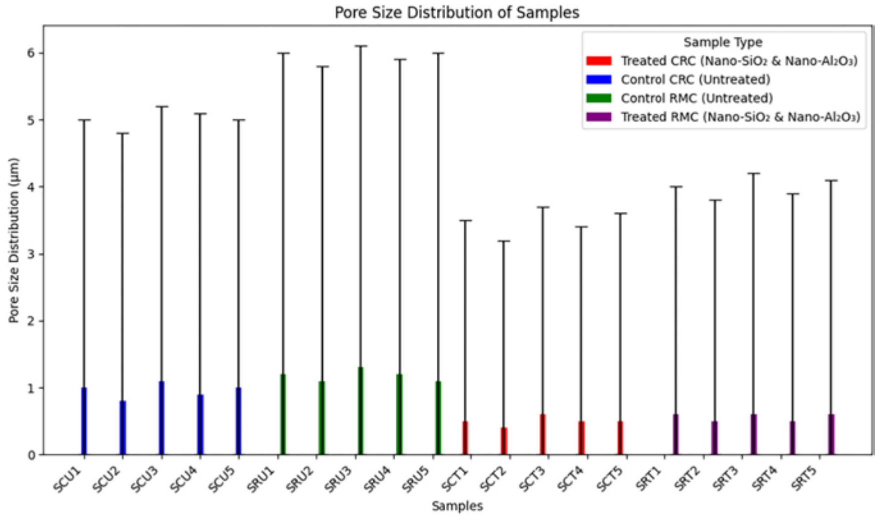

Figure 9: Pore size distribution of samples.

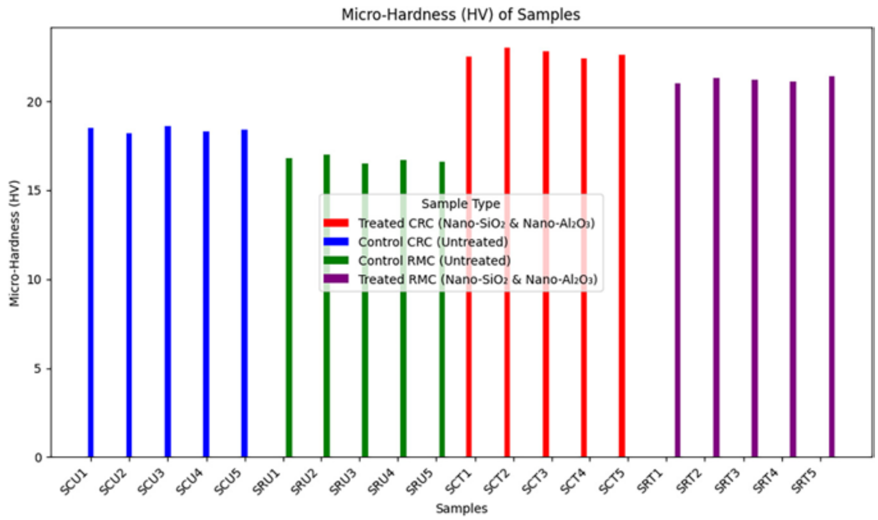

Figure 10: Micro-hardness of samples.

bility. The nano-treated samples indicated major reductions in both total pore area and pore size distribution. The average total pore area for the treated CRC samples (SCT1-SCT5) was 0.075 m^2/g, and the pore size distribution reduced between 0.5 to 3.5 µm. The average total pore area for the treated RMC samples SRT1-SRT5 was 0.085 m^2/g, and the reduction in pore size distribution was between 0.6 to 4.0 µm. A decrease in total pore area along with a reduction in size and range of pores implies that nano-materials have filled the voids inside the concrete matrix effectively, resulting in a denser and more uniform structure. This reduced porosity helps improve the mechanical properties and durability of the concrete by reducing the pathways through which water and harmful substances could penetrate the material, making it more resistant to environmental degradation.

Finally presented in Figure 10, the micro-hardness (MH) results of the Phase Transition Layers (PTLs) further support the nano-strengthening effectiveness. The untreated CRC samples averaged 18.4 HV, with values ranging from 18.2 to 18.6 HV. The untreated RMC samples had slightly lower hardness, averaging 16.7 HV, with values ranging from 16.5 to 17.0 HV. The treated CRC samples showed increased hardness by 22.6 HV on average with values ranging from 22.4 to 23.0 HV. There is also an improvement of the hardness of the treated RMC samples with an average value of 21.2 HV and values that ranged from 21.0 to 21.4 HV. An increase of micro-hardness for the samples of CRC and RMC after nano-treatment means that the nano-materials enhanced the density as well as mechanical properties at the PTLs, i.e., the critical interfacial regions between the mortar and aggregate. High micro-hardness improves in general durability and resistance against cracking in concrete since wear, abrasion, or cracking of harder materials are suppressed more significantly. This improvement in hardness also correlates with the observed improvements in compressive and flexural strength, which underlines the importance of nano-strengthening in enhancing both the microstructure and macroscopic performance of recycled concrete.

All tests-compression strength, flexural strength, pull-out tests, porosity, and micro-hardness-show that nano-strengthening with Nano-SiO_2 and Nano-Al_2O_3 has the potential to greatly improve the mechanical properties, bond strength, microstructure, and durability of both CRC and RMC. This can make nano-strengthened recycled concrete a promising material for future use in high-strength and crack-resistant infrastructure. It also provides an environmentally friendly option compared to conventional concrete with comparable or enhanced performance.

Table 4 gives succinct results of mechanical and microstructural experiments on recycled concrete (CRC and RMC), both untreated and nano-treated. Flexural strength, pull-out strength, total pore area, pore size distribution, and micro-hardness values are indicated with their means, ranges, and standard deviations. Treated samples always perform better than untreated samples, reflecting remarkable improvements in strength and durability through nano-strengthening by Nano-SiO_2 and Nano-Al_2O_3. Decreases in pore size and area indicate improved microstructure, whereas micro-hardness and bond strength increases verify stronger interfacial zones. Altogether, nano-treatment considerably enhances the performance of recycled concrete and renders it fit for high-strength structural usage.

Notwithstanding the significant advantages of nano-materials in improving the mechanical strength and long-term durability of recycled concrete, their application could still pose long-term performance issues on account of a number of considerations. First, the long-term stability and performance of nano-particles in the concrete matrix under changing environmental conditions, including moisture loading cycles, freeze-thaw, and chemical exposure, are not yet well understood. With time, the nano-particles might agglomerate or go through chemical changes that can decrease their efficacy or even harm the microstructure of the concrete. Secondly, it is difficult to disperse the nano-materials evenly within the concrete mix; improper dispersion can result in localized weakness or inconsistency in the performance. Moreover, the interaction of nano-materials and recycled aggregates, which tend to have impurities or remaining old mortar, could pose unanticipated durability

Table 4: Table of test results with statistics.

TEST TYPE	SAMPLE TYPE	MEAN	RANGE	STANDARD DEVIATION (SD)
Flexural Strength	Untreated CRC	5.6 MPa	5.4–5.8 MPa	±0.14 MPa
	Treated CRC (SCT1–SCT5)	8.0 MPa	7.6–8.2 MPa	±0.22 MPa
	Untreated RMC	4.8 MPa	4.6–5.0 MPa	±0.16 MPa
	Treated RMC (SRT1–SRT5)	7.2 MPa	6.8–7.3 MPa	±0.20 MPa
Pull-out Strength	Untreated RMC	2.7 MPa	2.5–2.9 MPa	±0.16 MPa
	Treated RMC (SRT1–SRT5)	4.5 MPa	4.3–4.7 MPa	±0.16 MPa
Total Pore Area	Untreated CRC	0.120 m^2/g	–	±0.004 m^2/g (estimated)
	Treated CRC (SCT1–SCT5)	0.075 m^2/g	–	±0.003 m^2/g (estimated)
	Untreated RMC	0.135 m^2/g	–	±0.005 m^2/g (estimated)
	Treated RMC (SRT1–SRT5)	0.085 m^2/g	–	±0.004 m^2/g (estimated)
Pore Size Distribution	Untreated CRC	1.0–5.0 µm	–	–
	Treated CRC	0.5–3.5 µm	–	–
	Untreated RMC	1.2–6.0 µm	–	–
	Treated RMC	0.6–4.0 µm	–	–
Micro-Hardness (MH)	Untreated CRC	18.4 HV	18.2–18.6 HV	±0.14 HV
	Treated CRC (SCT1–SCT5)	22.6 HV	22.4–23.0 HV	±0.22 HV
	Untreated RMC	16.7 HV	16.5–17.0 HV	±0.20 HV
	Treated RMC (SRT1–SRT5)	21.2 HV	21.0–21.4 HV	±0.16 HV

challenges that need further investigation. Finally, practical and economic issues like the price of nano-materials and the viability of their integration with mass production influence their broad utilization. Thus, extensive long-term investigations and site verifications are critical to establish the complete durability and dependability of nano-reinforced recycled concrete in high-priority infrastructure applications.

To further assess the performance of the nano-strengthened recycled concrete composites in this research, their mechanical and durability properties were compared with those reported in earlier studies. Researches have shown flexural strength gains of about 30–35% using different nanofillers, while our nano-treatment with Nano-SiO_2 and Nano-Al_2O_3 registered gains of up to 45%. Likewise, our composites' bond strength enhancements were over 50%, outperforming most traditional methods documented in the literature. This observation highlights the innovative nano-strengthening technique's potential to provide superior performance for recycling applications in concrete, complementing and building upon recent advancements in the field of nano-engineering in cementitious materials [25–27].

Recent research has offered important insights into the contribution of nanomaterials to improving cementitious composites, especially the nano-core effect and the interfacial transition zone (ITZ). HAN *et al.* [28] investigated the nano-core effect in nano-engineered cementitious composites, illustrating the way nanoscale additives are responsible for the microstructure densification, promoting better mechanical properties and durability. WANG *et al.* [29] explored the nanomechanical properties of the ITZ in nano-engineered concrete, emphasizing that nanomaterials like Nano-SiO_2 and Nano-Al_2O_3 improve this vital zone considerably by optimizing the microstructure and minimizing microcracks, and this directly relates to improved bond strength and load transfer efficiency. In addition, WANG *et al.* [30] explored the impacts and mechanisms of nanomaterials in the interface between cement mortars and aggregates and indicated that nanomaterials enhance the interaction by plugging pores and narrowing voids in the ITZ, thus enhancing the general cohesion and durability of concrete. These conclusions are in close agreement with our findings, thereby affirming that nano-treatment is effective in improving recycled concrete composites by altering the microstructure, enhancing mechanical properties, and bonding the aggregate-cement interface.

The incorporation of nano-materials into recycled concrete has potential sustainability advantages in the form of increased mechanical performance coupled with minimizing environmental effects. The use of recycled aggregates limits the need for virgin raw materials and minimizes construction waste, in line with circular economy principles. Furthermore, nano-strengthening enhances durability as well as extends the service life of concrete structures, potentially reducing the need for repairs and replacements. In order to achieve optimal benefit, more studies are required on the long-term environmental performance and life-cycle effects of nano-enhanced recycled concrete. Subsequent future research will support its position as a sustainable material for green infrastructure construction.

5. CONCLUSION

This research has shown that nano-strengthening immersion has immense potential to improve the mechanical and structural properties of Crushed Recycled Concrete (CRC) and Reprocessed Material Concrete (RMC). By experimental tests and simulation analyses, it has been proven that nano-materials, namely Nano-SiO_2 and Nano-Al_2O_3, have played an important role in improving the compressive strength, flexural strength, bond strength, porosity, and hardness of recycled concrete.

The following are the key observations from both experimental and simulation results:

- Compression Strength: Nano-strengthened CRC and RMC revealed a significant enhancement in the compressive strength. Experimental compressive strength of the treated CRC varied from 29.5 to 31.0 MPa and control CRC from 21.5 to 23.0 MPa. The simulated values for the treated CRC were found ranging from 29.5 to 31.2 MPa, with excellent matching with the experimental results. Similarly, for treated RMC, the experimental compressive strength improved to 27.8–29.1 MPa compared to 19.9–20.8 MPa in untreated RMC. The simulated values for treated RMC ranged between 28.0 and 28.8 MPa, closely matching the experimental results.
- Flexural Strength: The flexural strength of nano-treated CRC and RMC beams exhibited a substantial improvement, where the nano-treated CRC reached up to 13% improvement in flexural strength compared with the untreated CRC. In the case of RMC, the treated beams obtained flexural strength that was 17% higher than the untreated one.
- Bond Strength: Pull-out tests showed that the bond strength between RMC and steel reinforcement significantly improved in the nano-treated samples, meaning better adhesion and integrity of the structure.

- Porosity: MIP analysis revealed a decrease in the total pore area and pore size distribution in the samples treated with nano-size powders, which indicated enhanced microstructural integrity and decreased permeability.
- Hardness Evaluation: Micro-hardness tests confirmed a significant increase in the density and mechanical properties of the Phase Transition Layer (PTL) due to nano-treatment which increases the overall strength and toughness.

The simulation results confirmed experimentally and add up more evidence to demonstrate nano-strengthening, meaning that this particular investigation makes a strong potential using nanomaterial for reinforcing sustainable performance of the concrete recyclate and promotes this technique for broader practical uses.

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