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Influence of Nanoparticles and PVA Fibers on Concrete and Mortar on Microstructural and Durability Properties

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Abstract: Nanoparticles are one of the effective methodologies implemented in concrete technology. The main objective of this research is to study the influence of nano alumina with different percentage variations ranging from 1% to 3% along with the incorporation of PVA fibers. From the mechanical properties test, the optimum dosage was determined to further study the durability behavior. This research work also investigates the hybridization of two nanoparticles such as nano silica (NS) and nano alumina (NA). The results show that the increasing quantity of NA reduces the compressive strength of the mortar due to agglomeration (cluster of particles), which results in a greater molecular attraction force. From the test results, it is concluded that the optimum dosage has been attained with an addition of 2% NA with 0.3% PVA. The compression strength test results at 14 days and 28 days reveal that the addition of NA tends the mineral admixture to react at early ages in the hydration process, which produces a new chemical compound to fill the pores. The rapid chloride penetration (RCPT) test results at 28 days significantly improved with the incorporation of nanoparticles due to their effective size and chemical reaction towards the other compounds. The test results from the hybridization of nanoparticles showed that the compressive strength was significantly enhanced compared to that of the control mortar and mortar with NA. They are effective up to certain limits beyond that addition, and the workability was reduced. Amongst all mixtures, the maximum compression strength has been attained for the mix with the addition of NA 0.5% and NS 2.5% comparatively. The microstructural properties of mortar were also studied through scanning electron microscope (SEM) analysis. The results showed that the incorporation of nanoparticles in the mortar matrix turns homogeneous with fewer pores and greater amount of hydration compounds; thereby, pore refinement has improved the hydration compounds remarkably.

Keywords: nanoparticles; nano alumina; nano silica; fibers; durability; microstructural property; EDX

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1. Introduction

Concrete is the most-used material for construction; it is indeed a widely used material in the civil engineering industry due to its many advantageous properties. In addition to its durability and moldability, concrete is also fire-resistant, has good thermal mass, and can be produced with industrial by-products, which makes it a sustainable option for construction. Furthermore, concrete requires less energy to be produced compared to other building materials such as steel and has a relatively low cost and robustness. Even in this updated generation of lightweight structures, concrete is the only construction material that is being used for the construction of mass structures with traditional or modern concrete. Very new inventions are made using 60% less energy and CO_2 emissions over the time of a structure than conventional concrete due to the limitations [1]; because of the recent advancements in the characterization technique, the behavior of their chemical materials is divided into a variable length scale ranging from micro scale to macro scale [2,3]. This emphasizes the realistic behavior of cementitious material at the sub-micrometer scale, which is demonstrated to magnify their micro as well as macro properties [4]. The potential usage of particles on a nanometer scale has generated significant scientific interest, leading to improved attention on nanotechnology. Nanoparticles are used as a replacement for cement to improve the strength and microstructural properties of the concrete [5,6]. These replacement levels take precedence to change the properties of concrete in two ways: one is physical, and the other is its chemical and phase compositions [7,8]. Nanoparticles such as (1) nano silica, (2) nano alumina, (3) nano titanium, (4) nano clay, (5) nano zinc, etc., and mineral admixtures like ground granular blast furnace slag, rice husk ash, fly ash, and silica fume are commonly used in cementitious applications. The economic and environmental advantages of nanotechnology, along with its capability to decrease the micro and macro porosity of the matrix, have contributed to its increasing reverence in the construction field [9]. The addition of mineral admixtures in concrete can improve its flowing ability and absorb the water present in the free space around the surface of the particles along with the utilization of nanoparticle incorporation. As a result, the water-to-binder ratio within the matrix decreases and the strength parameters increase [10–12]; as stated in the previous study, nano silica has more pozzolanic activity than silica fume [13,14].

In addition, nanoparticles also improve the durability of concrete. The main mechanical property, such as the compressive strength enhanced by the addition of nano alumina, was reported [15,16]; on the other hand, most of the studies showed that an excessive amount of nano alumina has an adverse effect on the strength properties rather than durability performance [17–20]. This may be due to the excess quantity of nanoparticles confined to the extension of $Ca(OH)_2$ crystals. The addition of mineral admixtures in the nanoparticle concrete enhances the pozzolanic reaction and workability of the matrix.

Mostly, the addition of nanoparticles in concrete reduces the flexural property, which results in the initiation of cracks with the application of load, and this can be overcome by the utilization of fibers like the low or high modulus of elasticity fibers [21]. A study on enhancing the crack-resistance behaviors of concrete materials by the combination of TiO_2 nanoparticles and waste plastic fibers was carried out and reported that the addition of fibers reduces the propagation of cracks. The incorporation of glass and polypropylene fibers on both the mechanical and microstructural characteristics of concrete has increased the crack resistance under the jet impact load [22,23]. The findings of the study offer valuable insights into the potential advantages of utilizing low-modulus elasticity fibers in enhancing the performance of concrete [24–28]. Henceforth, the nanoparticles influence the fresh, mechanical, and microstructural properties of concrete with the inclusion of supplementary cementitious material. In concrete, ettringite crystals can develop in porous areas, and if they become sufficiently thick, they can interlace with each other to form a complex network. Therefore, it reduces the pore size and increases the strength and durability of the concrete. Ternary composites typically include three components: cement, silica fume, fly ash, or similar materials, which are used to improve the mechanical properties of concrete [29–32]. Microstructure analysis is commonly performed using X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM) to correlate the microstructure with its mechanical properties. Although prior to mixing, some nanoparticles must be sonicated for dispersion and agglomeration to counterfeit the period of mixing during the cement hydration phase.

The microstructures of the cement paste at the interfacial transition zone (ITZ) were examined using SEM to evaluate the weak zone of the concrete. In ordinary Portland cement (OPC) concrete, porous paste structures can be identified at the ITZ, where crystalline calcium hydroxide (CH), needle-shaped ettringite, and amorphous calcium silicate hydrates (C-S-H) are distinguishable [33–36] from the mortar. It can also be affected by the particle shape and size and the method of dispersion. Because of its extremely small size, the workability of the mixture containing greater amounts of nano silica was found to be reduced [37–39]. However, the same dosage of nano titanium caused less reduction in workability when compared to nano silica, which is attributed to the larger specific surface area of the nano silica particles [40]. The utilization of nanoparticles in concrete can offer several benefits, including improved mechanical properties, increased durability, and reduced environmental impact. For example, the incorporation of nano alumina can increase the compressive strength and fracture toughness of concrete, while the addition of nano silica improves the workability with the reduced water–cement ratio.

In general, the incorporation of nanoparticles in concrete has the potential to transform the construction industry by offering more robust, resilient, and sustainable concrete structures [41]. The focus of this study is to investigate the durability and microstructural properties of mortar with the incorporation of nano silica with and without polyvinyl alcohol fibers (PVA). There is a dearth of knowledge in the construction industry with the addition of hybrid nanoparticles along with the utilization of fibers. Henceforth, this study has also focused on evaluating the addition of two nanoparticles such as nano silica (NS) and nano alumina (NA) from the optimization of mixtures through mechanical property tests. Eventually, the microstructural properties were investigated for the optimized dosage of the nanoparticle mortar specimens to evaluate the strength parameters from the chemical composition phase. This paper also aims to study the durability properties accompanied by the water absorption and rapid chloride penetration test to evaluate the performance and influence of NS and NA with the incorporation of PVA fibers. The novelty of the current research is to utilize hybrid nanoparticles such as NS and NA along with the incorporation of PVA fibers, which enhances the mechanical, durability, and microstructural properties of concrete.

2. Material and Methods

2.1. Materials and Mix Proportions

The cementitious materials used in the research work are ordinary Portland cement (OPC), nano silica (NS), nano alumina (NA), ground granulated blast-furnace slag (GGBS), and polyvinyl alcohol fibers (PVA). These cementitious materials are mixed with fine and coarse aggregates along with water to form a solid and unified mass, which fills any small voids within the concrete. In this work, an OPC of 53 grades was utilized, conforming to Indian standard (IS) 12269:2013 [42]. The specific gravity test has been conducted by IS:2720 Part 3 [43], while the fineness test adheres to IS 4031 Part 1 (1996) [44]. Similarly, the consistency test was also performed as per the IS: 4031 Part 4 (1988) [45], and the setting time was also calculated according to IS: 4031 Part 5 (1988) [46]. GGBS is a by-product of the iron-making process and is produced by quenching molten iron slag from a blast furnace with water or steam. It has a chemical composition that is equivalent to cement. It is responsible for reducing thermal cracks in concrete as well as increasing the damage resistance. The chemical compositions of the cementitious materials are shown in Table 1 and their physical properties are shown in Table 2.

Table 1. Chemical composition of cement and GGBS.

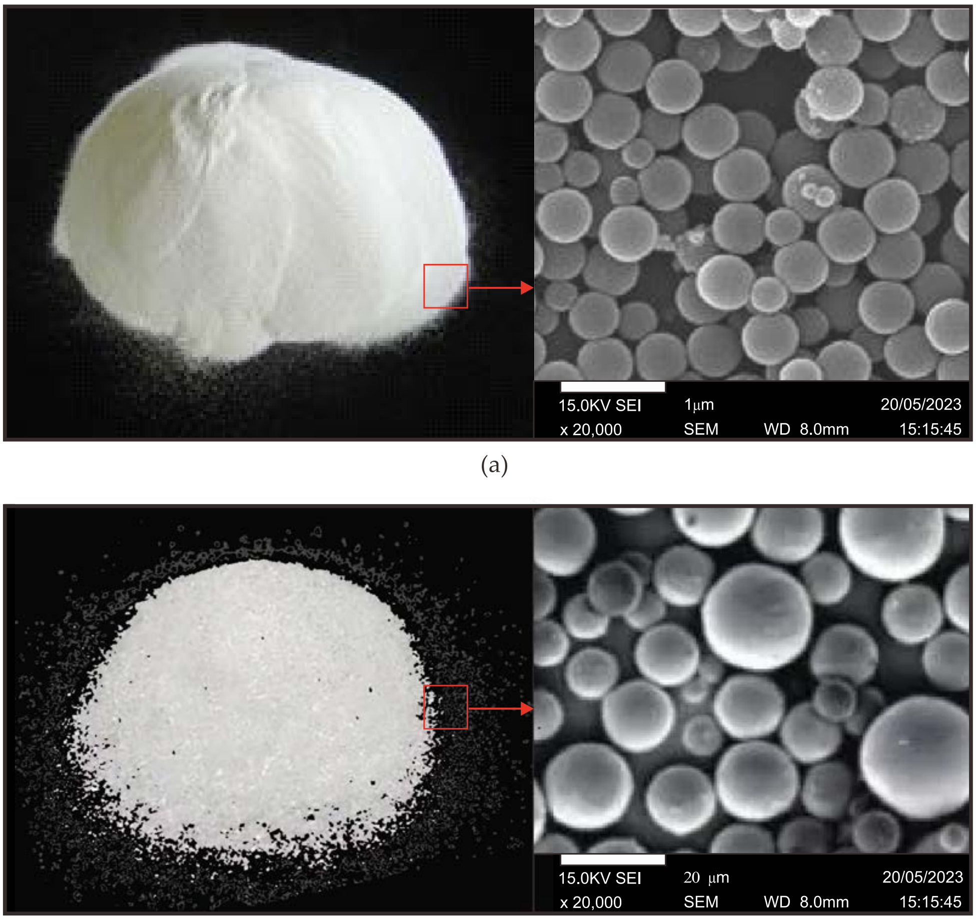
Material	Calcium Oxide (CaO)	Silica (SiO_2)	Ferric Oxide (Fe_2O_3)	Sulfuric Anhydride (SO_3)	Alumina (Al_2O_3)	Magnesium Oxide (MgO)
Cement	64.85	19.30	3.67	2.83	5.02	2.09
GGBS	36.98	34.57	0.49	-	18.62	7.76

Table 2. Physical properties of cementitious materials.

Material	Consistency (%)	Initial Setting Time (min)	Specific Gravity	Fineness (%)
Cement	32%	34	3.09	5.5%
GGBS	40%	2.32	54	34.5%

2.2. Nanoparticles and Fibers

Nano alumina: NA is formed directly from alumina and has a crucial role in regulating the setting time of cement in ultra-high-performance concrete. By incorporating NA, issues such as segregation and flocculation can be reduced. Several studies have highlighted the significance of the size, type, and mix proportions of nanoparticles in determining the performance of composites. On the other hand, its van der Waals force and electronic action can reduce the fluidity and strength of the concrete. This leads to the formation of clusters of calcium aluminosilicate (C-A-S-H) gel, which shortens the segregation and flocculation. A typical view of nano alumina and its microstructure is shown in Figure 1a. The chemical compositions and physical properties of NA are illustrated in Tables 3 and 4.



(a)

(b)

Figure 1. Typical view of nanoparticles: (**a**) nano silica and (**b**) nano alumina.

Table 3. Chemical compositions of nanoparticles.

Material	(Al_2O_3)	(Fe_2O_3)	(SiO_2)	(NaO_2)	Carbon Content (%)	Chloride Content (%)	TiO_2
Nano Alumina (NA)	99.0%	0.012%	0.013%	0.37%	-	-	-
Nano Silica (NS)	0.005	0.001	99.88	-	0.06	0.06	0.004

Table 4. Physical properties of nanoparticles.

Material	Specific Gravity	Particle Size (nm)
Nano Alumina (NA)	3.4–3.6	70–85
Nano Silica (NS)	2.2–2.4	17

Nano Silica (NS): Micro-based silica was used to produce NS, and the interaction between the nanoparticles and cement products is crucial for effective nano modification. The reactivity of NS can be influenced by two key structural properties: the degree of crystallinity and the degree of cross-linking. If the amorphous silica is contemplated as imperfect quartz, then the lattice potential of the matrix allows for the renewing energy for the pozzolanic reaction, which is more when atoms are in their minimum-energy positions. The chemical composition and physical properties of NS are presented in Tables 3 and 4. A typical view of NS and its microstructure is shown in Figure 1b.

Fibers: PVA fibers are high-performance reinforcement fibers for concrete. They are monofilament fibers that diffuse throughout the concrete matrix; it is fabricated from a multi-directional fiber network that sovereignty shrinkage, and abrasion, and preserves them from thermal expansion and contraction. The physical properties of PVA fibers are illustrated in Table 5. A typical view of PVS fibers is shown in Figure 2a,b. Polycarboxylate ether-based (PCE) superplasticizer (SP) was utilized to reduce the amount of water and enhance the fluidity and dispersion of nanoparticles. In this research work, a various mix combination of NA and GGBS with and without PVA fibers was considered to study the strength and durability performance.

Table 5. Physical properties of the polyvinyl alcoholic fiber.

S. No	Property	Value
1	Aspect ratio (L/D)	166.67
3	Specific gravity	1.3
4	Tensile strength (MPa)	1600

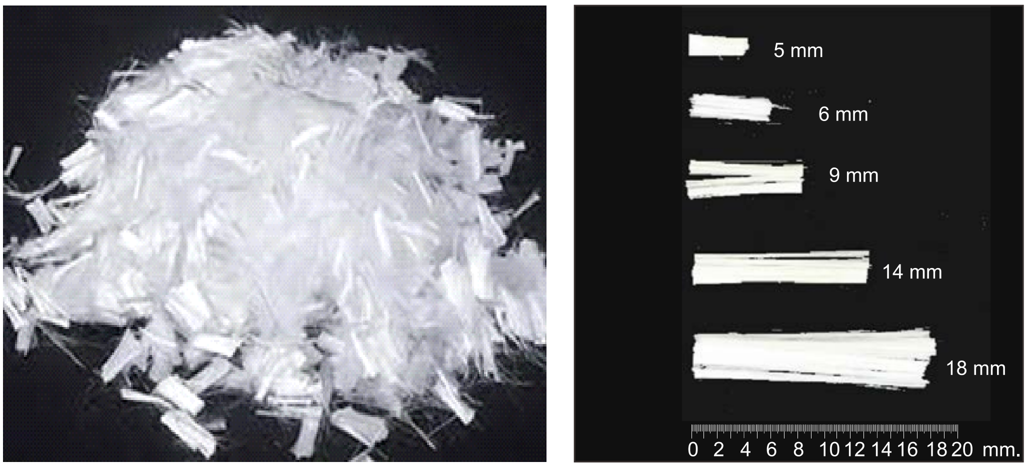


Figure 2. Typical view of polyvinyl alcohol fiber (**a**) and various lengths (**b**) used in this study.

3. Experimental Program

3.1. Mixing of Nanoparticles

A total of twenty-one different mixes were prepared, each with varying amounts of GGBS, NA, NS, PVA, and SP. The percentage of GGBS was adjusted between 10% and 15% by weight of cement. The percentage of nanoparticles varied from 0% to 3% along with the addition of different percentage variations of PVA fibers from 0% to 0.3% by weight of cement. The quantity of SP varied from 0.9% to 2% by weight of cement. A constant water to binder ratio (w/b) of 0.49 was maintained across all the mixtures. The detailed mix proportions of mortars are shown in Table 6. The casting of mortar specimens is shown in Figure 3.

Table 6. The detailed mixture proportions of mortar with and without PVA fibers.

Mix Designations	Cement (kg/m^3)	GGBS (kg/m^3)	PVA (kg/m^3)	NA (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
M_C	445	-	-	-	1366.5	217.8	0.9
M_{CG1}	400.5	44.50	-	-	1366.5	217.8	0.9
M_{CG2}	387.25	66.75	-	-	1366.5	217.8	1
M_{CG1A1}	396.05	44.50	-	4.45	1366.5	217.8	1
M_{CG1A2}	391.59	44.50	-	8.91	1366.5	217.8	1
M_{CG1A3}	387.15	44.50	-	13.35	1366.5	217.8	1
M_{CG2A1}	373.80	66.75	-	4.45	1366.5	217.8	1
M_{CG2A2}	369.34	66.75	-	8.91	1366.5	217.8	1
M_{CG2A3}	364.90	66.75	-	13.35	1366.5	217.8	1
$M_{CG1A1PVA}$	396.05	44.50	1.33	4.45	1366.5	217.8	2
$M_{CG1A2PVA}$	390.26	44.50	1.33	8.91	1366.5	217.8	2
$M_{CG1A3PVA}$	385.82	44.50	1.33	13.35	1366.5	217.8	2
$M_{CG2A1PVA}$	372.47	66.75	1.33	4.45	1366.5	217.8	2
$M_{CG2A2PVA}$	368.01	66.75	1.33	8.91	1366.5	217.8	2
$M_{CG2A3PVA}$	363.62	66.75	1.33	13.35	1366.5	217.8	2

Note: M_C *represents control mortar*, $M_{CG1,2}$ represents mortar with 10% and 15% addition of GGBS, $M_{CGA1,2,3}$ represents mortar with 10% GGBS and 1% to 3% of NA, $M_{CG1A1PVA}$ represents mortar with 10% and 15% GGBS and 1% to 3% NA with PVA fibers.

(**a**) (**b**) (**c**)

Figure 3. Experimental procedure of mortar mixing and casting. (**a**) Mixing of materials. (**b**) Casting of specimens. (**c**) Preparation of specimens for testing.

Specimen preparation and curing: Material mixing and specimen preparation were performed in the laboratory. The cement mortar was mixed in a rotary mixer. Nanoparticles are not easy to mix homogeneously.

(i) In the preparation of the mortar mixture, the nanoparticles were not added directly to the dry mixture. Instead, they were mixed with the water that had already been combined with the superplasticizer and rotated at a higher speed for 1 min.

(ii) Once the nanoparticles were mixed with the water and superplasticizer, the cement and GGBS were added to the mixer and mixed at a medium speed for 30 s. Following this, the sand was gradually added to the mixture.

All the ingredients were added to the mixture and further mixed at a high speed for 1 min. For each mixture, a total of 6 cube specimens were cast of size $70.6 \times 70.6 \times 70.6$ mm^3. All the specimens were cured in water for 14 days and 28 days. The specimens were tested using a universal testing machine (UTM) with a capacity of 1000 kN.

3.2. Test Procedure

The compressive strength values of the mortar specimens, along with the corresponding variation in strength at different curing days, have been tested and the average of three specimens was considered. Further, the compressive strength of concrete was carried out based on the optimum results obtained in the mortar specimens and the test was conducted as per the IS code [47].

To study the durability property of the concrete, the (RCPT) test was performed as per ASTM C1202 [48] standard to analyze the resistance to the penetration of chloride ions. The test was regulated by situating a 100 mm diameter concrete cylinder into the sample cells containing 3.0% salt solution and 0.3 N sodium hydroxide solution. A voltage of 60 V DC is sustained across the ends of the sample throughout the test and the charge that passes through the sample is recorded. A qualitative rating can be made of the concrete's permeability based on the charge.

4. Results and Discussions

4.1. Compressive Strength

Figure 4a,b show the compressive strength of the mortar specimens with and without PVA fibers for all the mixtures. The test results showed that the compressive strength increases with the incorporation of PVA fibers and NA, whilst most of the researchers revealed that the mineral admixture addition improves the later strength comparatively. The addition of NA in the concrete along with the GGBS enhances the reaction at the early ages, which results in an improved compression strength. The composite matrix is homogeneous in nature with the formation of hydration compounds like C-S-H and C-H gel, which are responsible for the strength properties. With the addition of nanoparticles, pore refinement has increased along with the unhydrated cement particles, which results in a denser mortar matrix. From the compression strength results, the optimum dosage has been determined and the concrete mix was designed for 40 MPa concrete. Concrete mixtures with the addition of GGBS, NA, and PVA fibers were cast only for the optimized dosage, as shown in Table 7.

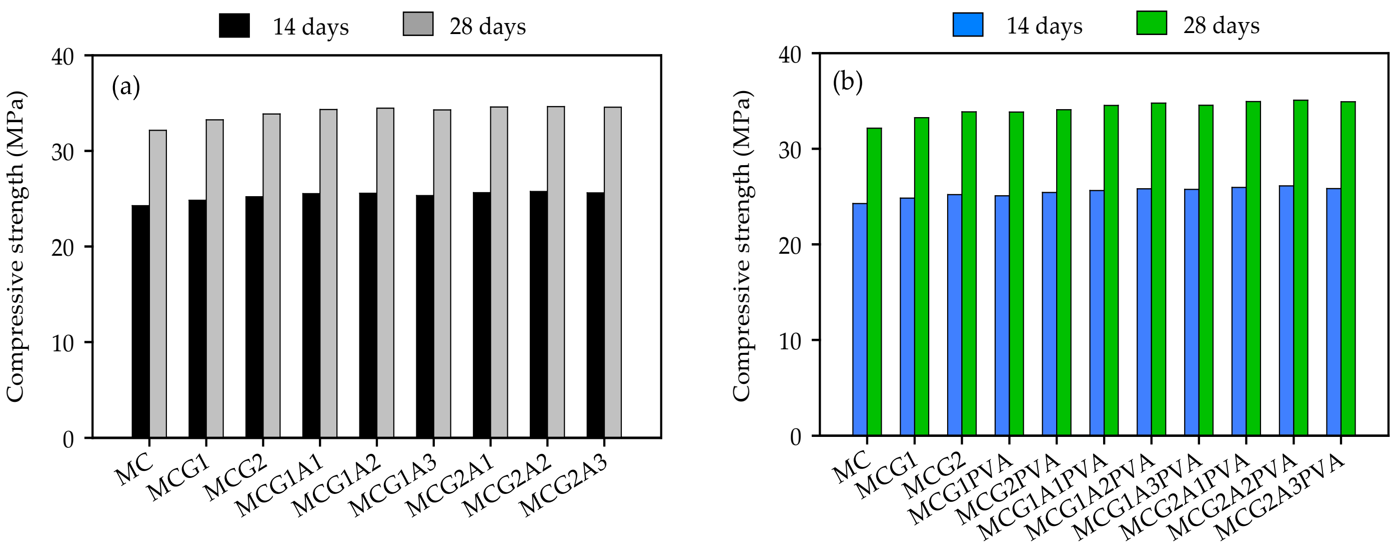


Figure 4. Compressive strength of mortar specimens. (**a**) Compressive strength of mortar specimens without PVA fibers. (**b**) Compressive strength of mortar specimens with PVA fibers.

Table 7. Mix proportions of 40 MPa concrete for the optimized dosage of mortar specimens.

Mix Designation	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	GGBS (kg/m^3)	NA (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Compressive Strength (MPa)—14D	Compressive Strength (MPa)—28D
M_C	410.0	640	1220	-	-	201	6.12	28.71	39.56
$M_{CG1A1PVA}$	372.4	640	1220	66.5	4.1	201	8.12	33.87	41.65
$M_{CG2A2PVA}$	368.0	640	1220	66.5	8.2	201	10.12	36.82	44.33

From the concrete compression strength results (Table 7), it has been observed that the addition of 15% GGBS and 2% NA along with the incorporation of PVA fibers attained the maximum compressive strength of 44.33 MPa with a percentage increase of about 12% when compared to the control concrete mix. The reason may be attributed to the crack resistance with the application of load from a low stress level to high stress level and the nanoparticle along with the fiber restrains the microcracks in the low stress level, which reduces the propagation of cracks to the macro level.

Furthermore, this study also investigated the hybridization of nanoparticles (NA and NS) to evaluate the performance of the mechanical and microstructural properties of the mortar specimens. Table 8 shows the mix proportions of the hybrid NA and NS mortar specimens with the total fiber volume fraction of 1%, 2%, and 3% with different combinations. Figure 5 shows the compression strength of the hybrid nanoparticle mortar specimens for 14 days and 28 days. From the figure, it was observed that the compressive strength of the hybrid NA and NS mortar specimens showed a higher performance compared to that of the control as well as the mono nanoparticle mortars. The incorporation of NA [8] enhances the feasibility of nanoparticles on the binder phase orientation and pore structure refinement. Also, the addition of ultrafine materials such as NA and NS reduces the amount of cement by replacing it on a weight basis, thereby improving the binding effect [26] in concrete.

Table 8. Mixture proportions of nano alumina and nano silica hybrid mortars.

Mix Designations	Cement (kg/m^3)	GGBS (kg/m^3)	NA (%)	NS (%)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
H_{Y1}	396.05	66.75	0.5	0.5	1361.15	217.6	1.7
H_{Y2}	391.60	66.75	1	1	1361.15	217.6	1.9
H_{Y3}	391.60	66.75	1.5	0.5	1361.15	217.6	1.9
H_{Y4}	387.15	66.75	0.5	1.5	1361.15	217.6	1.9
H_{Y5}	387.15	66.75	0.5	2.5	1361.15	217.6	2.1
H_{Y6}	387.15	66.75	2.5	0.5	1361.15	217.6	2.1
H_{Y7}	387.15	66.75	1.5	1.5	1361.15	217.6	2.1

Note: H_{Y1} *represents* mortar with 15% GGBS, 0.5% NA, and 0.5% NS followed by varying the percentage of NA and NS with the total fiber volume fraction as 1%, 2%, and 3%.

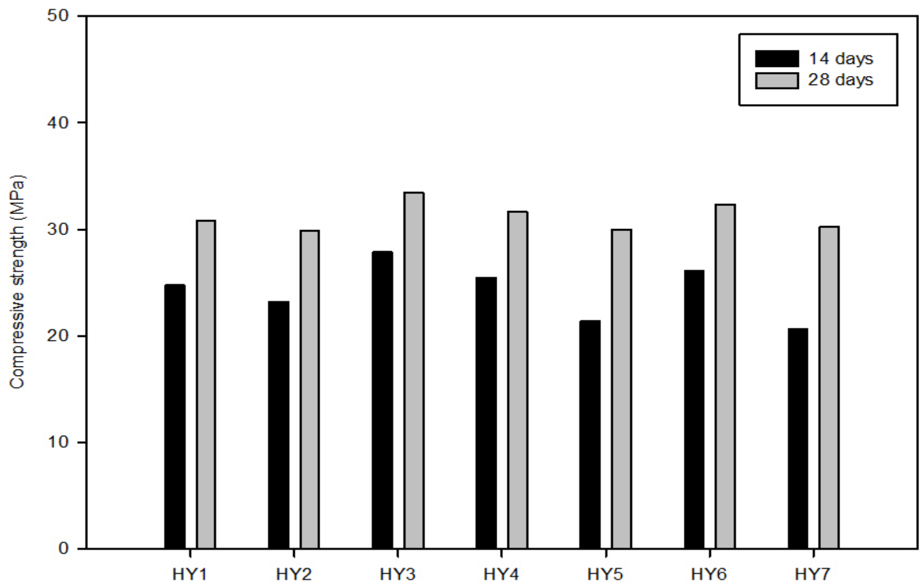


Figure 5. Compressive strength of hybrid mortar mixtures.

However, using only fibers in the mortar matrix reduces the propagation of cracks and increases the pore size of the specimen without nanoparticles. This is due to the length of the fibers, which are typically 5 mm long. While some fibers can easily mix with the cement, others do not disperse easily and need to be separated individually. This can result in less homogeneity and be responsible for the propagation of macro cracks along the surroundings of fibers. With the presence of nanoparticles in the matrix, macro cracks were restrained due to their micro size and high specific surface area.

This is consistent with the findings from the rheology analysis, which measures the flow and deformation behavior of materials. However, the study found that the mechanical properties of the samples were not significantly affected by the nanoparticle addition in the range tested. This suggests that the improvements in the hydration kinetics and rheology have not been translated to significant changes in the mechanical performance of the cementitious material [32]. The hydration process has also been increased by the addition of NS by the pozzolanic reaction with the densification of pore structures.

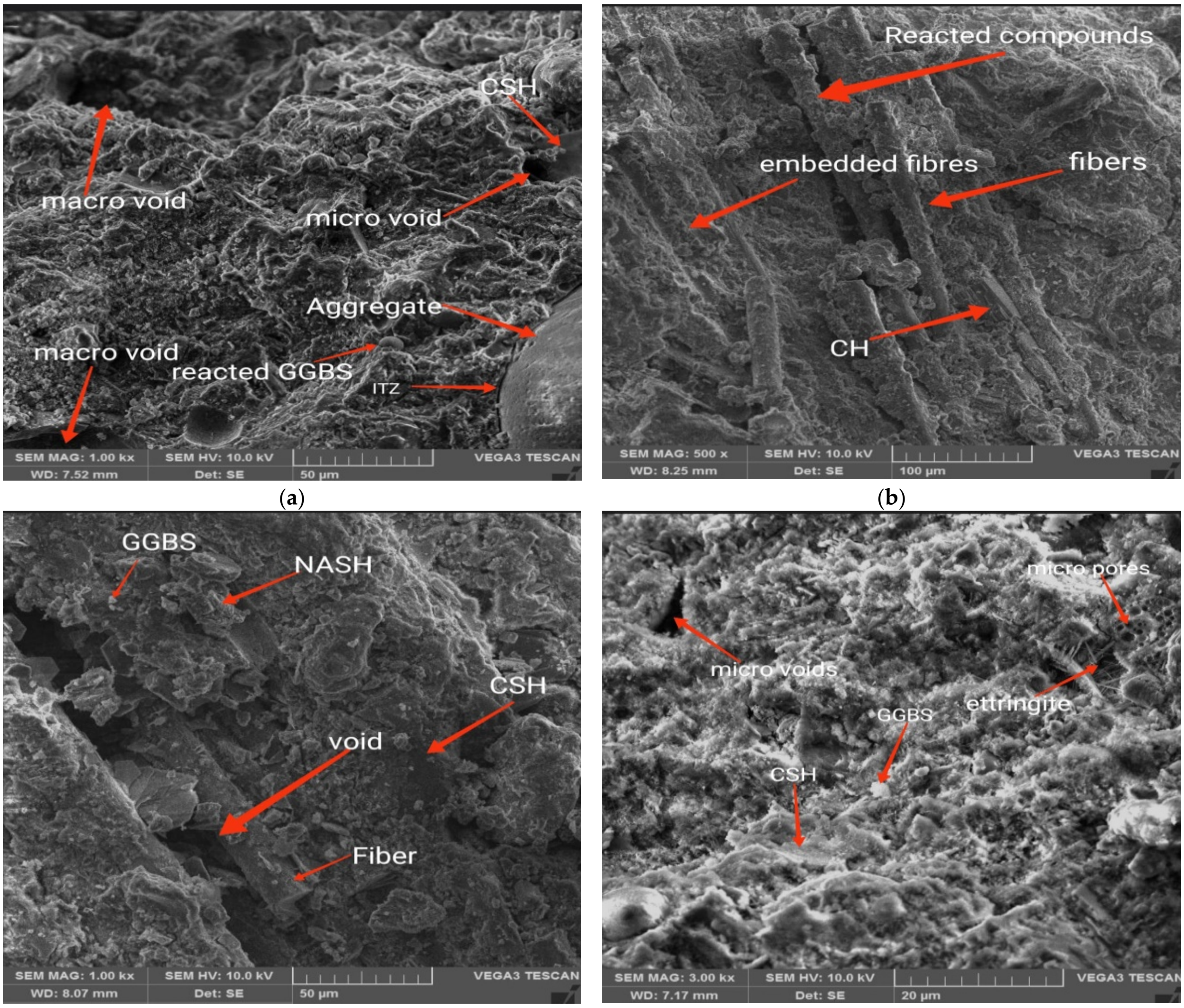
4.2. Microstructural Properties

The microstructural properties have been performed for certain samples that had higher compressive strength values, as shown in Figure 6. The SEM images demonstrate that up to a 3% addition of NA could be utilized effectively in mortars [32]. The addition of NS increased the hydration process and led to a reduction in the pore size and voids, which is clearly visible in the SEM analysis (Figure 6c). This refinement was attributed to the pozzolanic activity and filling ability of NS into the pores, which also influences the hydration rate in the mix. The cement hydration accelerated through the acceleration periods and deceleration periods. They devour the $Ca(OH)_2$ compound on the other hand, which functions as nucleation sites, further increasing the hydration process.

The microstructural property of the mortar matrix is clearly shown in the above images (Figure 6a) with the presence of micro and macro voids, along with the formation of CSH gel in the matrix; this is due to the absence of nanoparticles. The ITZ formation is shown crystal clear in the image around the aggregate and some number of compounds, which are not reacted and some of them are partially reacted. Figure 6a shows the SEM analysis with the presence of NA, which increases the homogeneity along with the fewer micro pores visible, which may be due to the improper dispersion and due to the agglomeration that occurred between the particles; it also shows the early formation of ettringite, which increases the strength. The energy dispersion is also seen in the figure at a particular area with the amount of energy dispersion. Due to the presence of fibers in the matrix, it shows a tight and compacted bonding in between the materials, which increases the load resistance and makes the structure good for bonding as well as tensile property. From Figure 6d, it can be observed from the SEM image of the hybrid matrix that there was no such pattern, which causes the degradation of the microstructural property and compressive strength with the formation of nano alumina silicate hydrated (NASH) gel.

The ettringite formation is clearly visible in Figure 6d, with hybrid nanoparticles, a needle-like structure, and ettringite formation responsible for reducing the pores. The percentage of both NS and NA is greatly effective in the SEM analysis, with both having their individual function and their chemical composition also being different but with the combination of various percentages attaining a better strength in terms of the durability and microstructural properties. The images with hydrated gel along with micropores and ettringite formation [13] reveal that the kinetics of hydration of the samples with varying amounts of NS and NT followed the same trend as the rheology results. Samples with higher amounts of NS and NT showed significant changes compared to those without nanoparticles.

However, the addition of nanoparticles did not significantly affect the mechanical properties. In the SEM analysis, it is clearly observed that the addition of fibers in mortar increases the strength; hence, a dense structure has been formed with a smaller number of voids and cracks compared with the conventional samples. The study on nanoparticles received much attention and interest in wide industrial and civil engineering practices and revolutionized future developments [11].



(**a**) (**b**) (**c**) (**d**)

Figure 6. SEM image of mortar specimens. (**a**) SEM image of mortar $M_{CG2,}$ (**b**) SEM image of hybrid fiber specimen $M_{CG2A2PVA1,}$ (**c**) SEM image of $M_{CG2A2PVA1,}$ (**d**) SEM image of H_{Y6}.

4.3. EDX

EDX images of the control mortar, mortar with hybrid nanoparticles, and mortar with fibers are shown in Figure 7. EDX is used to find out the amount of energy dispersion that occurs to fill the vacancy in a shell; the energy is displayed by an electron beam, which projects the X-rays. The occurrence of silica content is greater compared to calcium content, which is due to when the electron beam hits the lower shell of an atom, where the electron dislocates the position from that arbitrary position to attract the other electron from the outer shell to fulfill the vacancy. As the electron dislocates from a high energy shell to a low energy shell, the difference between the relocation of an electron is given in the form of X-rays. It is varied for a particular element and transformation. Figure 7c shows that the addition of 15% GGBS, 2% NA, and 0.3% PVA increases the alumina content compared to silica compounds, which is responsible for the early reaction and enhanced strength. Silica compounds give later strength when calcium reacts with water and forms $Ca(OH)_2$ gel. Figure 7b gives the EDX image of the hybrid nanoparticles, which give a high silica content compared to that of the alumina compounds because the presence of NS was comparatively high. The study acknowledges the cost implications of using nanomaterials, but the enhanced mechanical properties, durability, and microstructural improvements achieved with the incorporation of nano silica and nano alumina justify their applications. The benefits, such as increased compressive strength, improved workability, reduced porosity, and better durability, contribute to the long-term performance and sustainability of concrete structures. These advantages can lead to reduced maintenance costs and extended service life of concrete structures, thereby offsetting the initial cost of nanomaterials. Moreover, the research provides valuable insights into optimizing the use of nanomaterials to maximize the benefits while minimizing the costs.

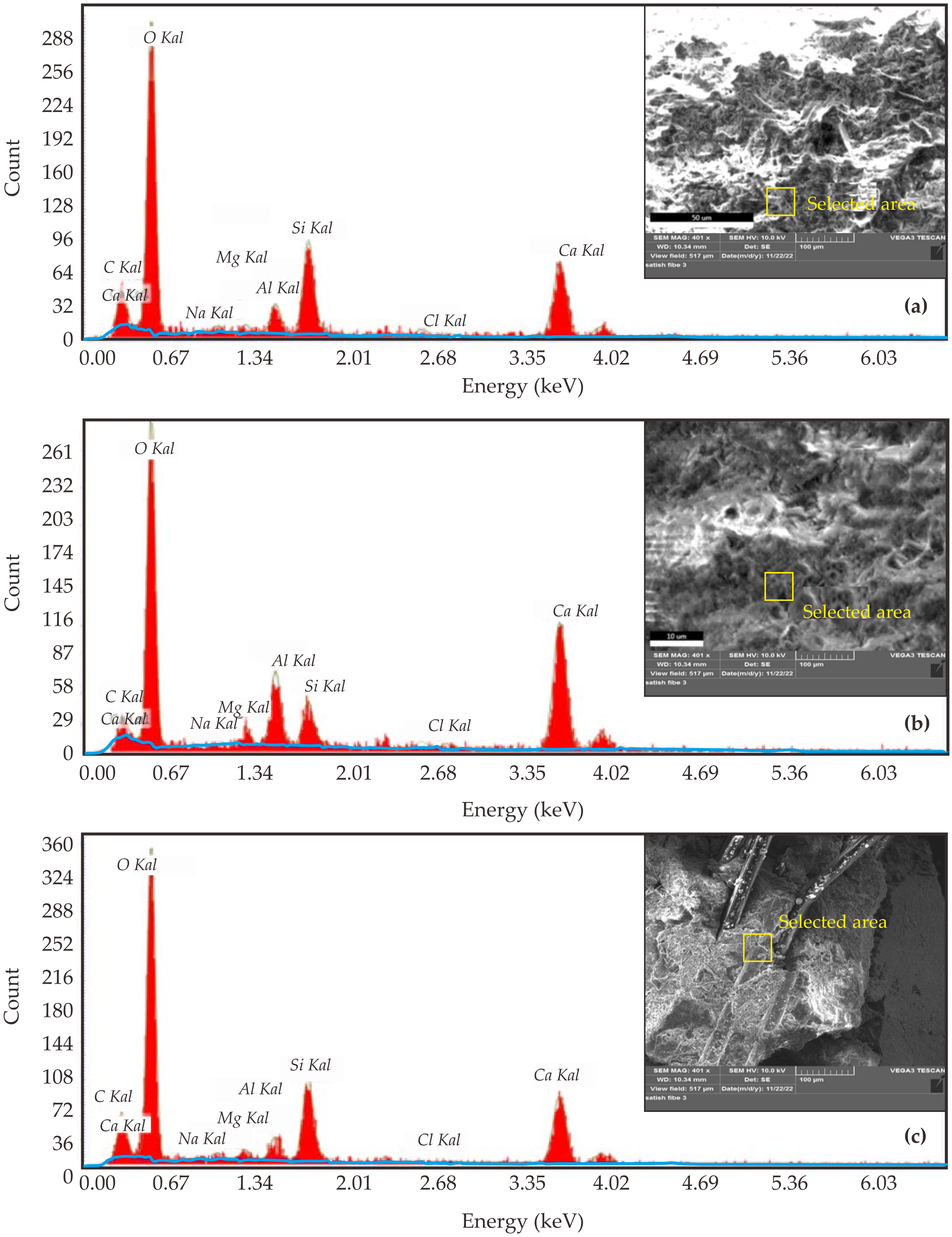


Figure 7. EDX image of mortar specimens. (**a**) EDX image of M_{CG2}, (**b**) EDX image of H_{Y6}, (**c**) EDX image of mix $M_{CG2A2PVA}$.

4.4. Rapid Chloride Penetration Test (RCPT)

From the mortar compressive strength values, the optimum dosage has been determined and the concrete of strength 40 MPa has been cast to carry out the durability property through the RCPT. The RCPT was conducted to investigate the durability characteristics of a concrete specimen for the optimized dosage as per the ASTM standard 1202C [48]. The greater amount of charge assessed in the depth of the concrete, the greater the number of voids and cracks present in the depth of the sample. Table 9 shows the test results of the RCPT for the concrete specimens with NA and PVA fibers. For a conventional 40 MPa concrete, the RCPT value is 2846 coulombs, due to the presence of voids and pores, which decreases the chloride penetration resistance. The concrete with the addition of 15% GGBS, 2% NA, and 0.3% PVA fibers has attained 1602 coulombs. As per the ASTM classification, the range between 1000 and 2000 is considered a low value and good resistance. A test was conducted to investigate the durability characteristics of a concrete material. The greater amount of charge assessed in the depth of the concrete, the greater the number of voids and cracks present in the depth of the sample. The addition of nanoparticles and PVA fibers increases the resistance to chloride penetration from the RCPT values, which are shown in Table 9.

Table 9. RCPT results of M40 concrete specimens with PVA fibers.

S. No	Mix Designation	RCPT Values (Coulombs)—14 D	RCPT Values (Coulombs)—14 D
1	M_{C}	2846	2516
3	$M_{CG2A1PVA}$	1982	1726
4	$M_{CG2A1PVA}$	1823	1602

5. Conclusions

In this experimental research work, the mechanical and durability properties of nano alumina and nano silica mortar mixtures with and without polyvinyl alcoholic fibers have been investigated. From the experimental study, the specific conclusions have been drawn:

- Amongst all mixtures of cement mortar using GGBS, it has been observed that the maximum compressive strength acquired for M_{CG2} is 25.21 MPa and 33.86 MPa at the age of 14 and 28 days, respectively. The percentage increment of the specimens was about 3.87% and 5.35% at the age of 14 and 28 days, respectively. The reason may be attributed to the filing effect of GGBS particles into the voids.
- For the addition of nano alumina in the mortar mixtures with different percentage combinations of GGBS, the maximum compressive strength was achieved for the mix M_{CG2A2} as 34.63 MPa at 28 days with the percentage increment of 7.75% when compared to that of the conventional mortar mixture.
- The maximum strength required for the mixture $M_{CG2A2PVA}$ is 35.08 MPa with the addition of 2% of NA, 15% of GGBS, and 0.3% of PVA fibers. The maximum percentage increase was about 9.15% when compared with a conventional mortar mixture. The percentage increase has been accompanied due to the confinement effect of the fiber and the restriction of the propagation of micro cracks in all stress levels.
- From the mechanical property results of the hybrid nanoparticle mortar mixtures, it has been clearly observed that the highest compressive is achieved for M_{H6} with the combination of 2.5% NS and 0.5% NA as 32.34 MPa with an increment of 7.4% as compared with the conventional mixture with the effect of the extremely lesser confinement of the pores.
- The maximum compressive strength of the obtained dosage of nanoparticle concrete is 44.33 MPa, which is attributed to the reduction in the pore size in the system.
- From the durability test, it is observed that the conductivity is much less due to the low porosity of the concrete with the addition of nanoparticles and PVA fibers.

- From the microstructural results, it is observed that an excess of CSH has been formed, which gives a further increase in the compressive strength for the mixture $M_{CG2.}$
- Based on the mechanical properties and microstructural properties for the optimized dosage $M_{CG2A2PVA}$ specimen, the strength development has been clearly visible in the SEM image, i.e., (1) reduction in pore size due to the presence of unhydrated cement particle and NA. (2) Increase in CSH gel in the structure.

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