Science and Technology Indonesia
e-ISSN:2580-4391 *p*-ISSN:2580-4405
Vol. 10, No. 1, January 2025

Research Paper

Effect of the Nano-Silica Addition on the Mechanical Properties of Polymer Concrete

Verinazul Septriansyah[1], Saloma[2], Siti Aisyah Nurjannah[2*], Anis Saggaff[2], Arie Putra Usman[2], Shek Poi Ngian[3]

[1]*Postgraduate Program, Department of Civil Engineering, Faculty of Engineering, Universitas Sriwijaya, Ogan Ilir, 30662, Indonesia*
[2]*Department of Civil Engineering, Faculty of Engineering, Universitas Sriwijaya, Ogan Ilir, 30662, Indonesia*
[3]*Construction Research Centre (CRC-UTM), Universiti Teknologi Malaysia, UTM Johor Bahru, Johor, 81310, Malaysia*
***Corresponding author**: sitiaisyahn@ft.unsri.ac.id

Abstract
The latest advances in science and technology have positioned nanomaterials at the vanguard of contemporary research. Nano silica (SiO_2) is an illustrative example of a nanomaterial extensively utilized in concrete manufacturing due to its properties as a pozzolan. The objective of this study is to elucidate the characteristics of nano silica and its effect on the performance of polymer concrete through experimental methods. X-ray diffraction (XRD) tests indicate that nano silica exhibits a high amorphous phase. Consequently, nano silica enhances the C−S−H gel formation reaction, producing more robust and denser specimens. The maximum compressive strength reached 45.23 MPa when adding 0.4% nano-silica with a specific gravity of 1573.33 kg/m^3. For comparison, concrete without nano silica had a maximum compressive strength of 40.05 MPa with a particular gravity of 1610.67 kg/m^3. Observation using a scanning electron microscope (SEM) showed that the nano-silica mixture exhibited excellent particle distribution as an activating agent that could enhance the strength of the specimens. Nevertheless, the observed reduction in compressive strength might be affected by several factors, including particle clusters and the presence of compounds carried by the fine aggregates that influence the mechanical properties of polymer concrete. Integrating nano-silica is pivotal in enhancing the compressive strength and reducing the specific gravity of polymer concrete specimens. The increased strength and decreased specific gravity render nano silica a promising additive for polymer concrete applications.

Keywords
Nano-Silica Characteristic, Nano Concrete, Nano-Silica Polymer

Received: 25 June 2024, Accepted: 24 September 2024
https://doi.org/10.26554/sti.2025.10.1.9-17

1. INTRODUCTION

Nano-sized materials have been investigated as alternatives to conventional binders, with smaller particle sizes than those typically observed in cement. The primary advantage of these smaller particle sizes is their capacity to enhance the hydration process, resulting in a denser and more robust material. Consequently, the incorporation of nanomaterials into concrete mixes has the potential to enhance the characteristics of the concrete itself, leading to a tighter and more robust microstructure than that observed in conventional concrete (Bautista-Gutierrez et al., 2019; Khan et al., 2022; Singh, 2020) These nanoparticles can improve the epoxy-resin strength by reducing the cracks that occurred due to highly cross-link reactions (Shameem et al., 2021).

Polymeric materials are macromolecular structured substances composed primarily of carbon and hydrogen atoms, forming long chains. Polymer concrete is a type of concrete that employs the innovative use of polymer resin as a binder, replacing the function of conventional cement. This concrete mix, consisting of polymer resin and fine aggregate, offers several advantages over traditional concrete, including enhanced mechanical characteristics, superior durability, enhanced adhesion, and a shorter curing time (Firda et al., 2023; Kiruthika et al., 2020).

Along with its development, nano silica (SiO_2) is considered a popular nanomaterial produced from micron-sized silica and is widely applied in concrete manufacturing. The application of nanotechnology in concrete, such as nano-silica, has attracted the interest of scientists and technologists. Nano silica can fill the pores with a smaller size, reducing the paste properties and optimizing the pore structure distribution. Incorporating even a tiny amount of nanosilica into concrete can increase compressive strength by up to 75% (Huseien et al., 2019). Epoxy has become the dominant material due to its superior properties, which can be optimized by adding various fillers. One of the most commonly used fillers is silica-based (SiO_2) (Linec and Music, 2019).

Concurrently, epoxy resin has emerged as a highly sought-

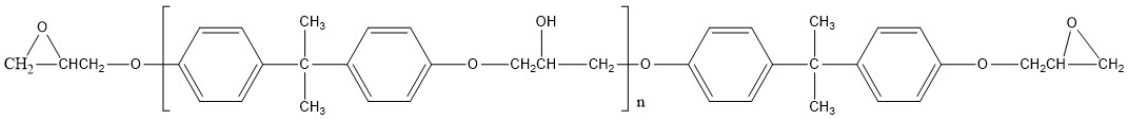

Figure 1. Chemical Structure of Bisphenol A Type Epoxy Resin

after material for hardening concrete. When combined with a hardener, epoxy oligomers form a three-dimensional substance of thermoset material (Ma et al., 2018). Epoxy resin is a valuable hardener material due to its low density, high compressive and tensile strength, and the ability of thermally activated epoxy resins to alter their functionality in response to varying temperature conditions (Lamm et al., 2018). Therefore, epoxy resin can speed up the drying process to help harden the polymer concrete. The type of epoxy resin depends on the chemical structure resistance process (Liang et al., 2018), as shown in Figure 1. The synthesized epoxy resin displays high thermal stability and superior mechanical strength., enabling extraordinary flexibility in mechanical properties (Chauhan and Tiwari, 2020). The epoxy resin typically used in making concrete is Bisphenol-A (DGEBA) combined with epichlorohydrin.

The proportion of hardener utilized in the hardening process can result in disparate mechanical properties of the epoxy resin. Utilizing a minimal hardener will reduce the viscosity of the epoxy resin, thus prolonging the hardening time. Conversely, using an excessively high percentage of hardener will cause the epoxy resin to become more brittle and its strength to diminish (Ferdous et al., 2020).

Fine aggregates play an essential role as fillers in the manufacture of polymer concrete. These aggregates, which have a grain size of less than 5 millimeters, are typically sand derived from rock decomposition. Its primary function is to prevent shrinkage in the mortar or concrete mix. Meanwhile, hardener catalyzes the hardening process of epoxy resin. The percentage of hardeners used can significantly affect the final mechanical properties of polymer concrete.

Recent research on the effect of nano-silica addition on the mechanical properties of polymer concrete opens up new avenues for developing construction materials. The novelty of this research lies in the combination of nano silica technology with polymer concrete, an area that has yet to be widely explored. This study aims to optimize the synergy between the advantages of nano-silica in filling micro-pores and increasing strength with the advantages of polymer concrete, which has high durability and strength. This study is anticipated to yield a novel composite material exhibiting enhanced mechanical properties, including augmented compressive strength, density, and durability. Moreover, this study has the potential to elucidate the interaction between nanoparticles and polymer matrices at the microstructural scale, which can serve as a foundation for further innovations in construction material technology.

2. EXPERIMENTAL SECTION

2.1 Materials

The study employed nano-silica, sand, epoxy resin, and hardener. The epoxy resin and hardener were employed in a ratio of 1:1 and 2:1, respectively, with a density of 1.08 g/cm^3. Nano silica is a powder with a particle size of ±54 nm to 140 nm and a density of 2.2 g/cm^3. Nano silica was added in several variations, namely 0%, 0.3%, 0.4%, and 0.5% by weight of epoxy resin. The sand was used at a ratio of 38% by weight of the total volume.

2.2 Methods

The present study employs a range of principal materials in producing epoxy mortar. The materials utilized in this study include nano-silica, sand, bisphenol A-based epoxy resin, and a hardener. Two distinct ratio variations of epoxy resin and hardener were employed, namely 1:1 and 2:1, with a density of 1.08 g/cm^3. The two materials above constituted 61.8% of the total mass of the mixture. Nano silica was included in four concentration variations, namely 0%, 0.3%, 0.4%, and 0.5% by weight of epoxy resin. The sand was used in up to 38% of the mixture, serving as an aggregate in the epoxy mortar.

This study adopted an experimental method to investigate the effect of variation in material composition on the properties of epoxy mortar. The mixing process of the materials was carried out through several stages. First, epoxy resin and nano silica (with varying concentrations of 0%, 0.3%, 0.4%, and 0.5%) were mixed and stirred for 5 minutes to ensure even distribution of nano silica. Next, hardener was added to the mixture and stirred for 5 minutes until homogeneous. In the last stage, sand was added to the mixture and stirred for 5 minutes to obtain a uniform mortar consistency.

After the stirring process and homogeneous mixture, the specimens were molded in 5 × 5 cm cube molds. The specimens were allowed to harden and stored for 28 days before a series of tests were conducted. Tests carried out include specific gravity measurement to determine the density of the material, compressive strength test to determine mechanical strength, X-ray diffraction examination using Rigaku MiniFlex 300/600 using X-Ray 30 kV, ten mA, scan range 5.0 - 90.0 degrees, scan speed 10.0 degrees/minute X-ray diffraction analysis (XRD) to determine the crystal structure and phase formed, FTIR analysis, and measurement using Scanning Electron Microscopy (SEM) to determine the microstructure of the material.

This method aims to analyze the effect of varying the epoxy resin and hardener ratio and the addition of nano-silica at various concentrations on epoxy mortar's physical, mechanical,

and microstructural properties. The test results are expected to provide a comprehensive understanding of the behavior and performance of epoxy-based composite materials with the addition of nano-silica and their potential application in industrial construction. The designation "BP N0%" refers to a polymer concrete formulation that does not contain nano-silica. In contrast, the designation "BPN 0.3%" denotes a polymer concrete composition incorporating 0.3% nano-silica into the epoxy resin matrix.

3. RESULTS AND DISCUSSION

3.1 Nano-Silica X-Ray Diffraction

X-ray diffraction analysis of the nano-silica samples revealed that the material consists of pure silica (SiO_2) with a tetragonal crystal structure. The diffraction pattern exhibited broad peaks and low intensity, indicating a tiny crystal size. This was confirmed by Williamson-Hall analysis, which showed an average crystallite size of approximately 13 Å, confirming that nano-silica is a nanocrystalline material this is illustrated in Figure 2.

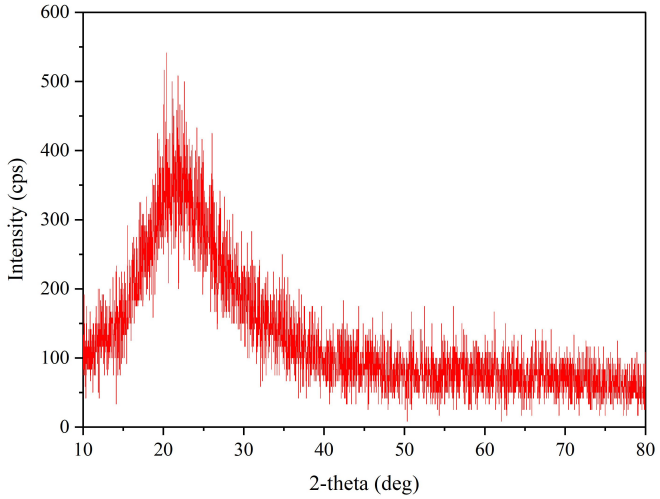

Figure 2. X-Ray Diffraction (XRD) Results of Nano Silica

In addition to the nanoscale dimensions, the sample exhibits a relatively high degree of lattice strain (6.8%), indicating distortions in the crystal structure. This combination of nanoscale dimensions and high strain could impart unique properties to the material (Ferdous et al., 2020), such as a large specific surface area and high reactivity, which could benefit applications such as catalysis or adsorption (Ismail et al., 2018).

Although the extreme peak broadening made analysis challenging, no other phases or crystalline impurities were identified, indicating the high purity of the sample. This is consistent with the results of the nano-characterization test, which showed a SiO_2 content of 99.8%, approaching ideal purity. The random orientation of the crystals (no preferential orientation) suggests that the material is likely to exhibit uniform properties in all directions. Incorporating nano-silica (SiO_2) particles into a material can enhance its strength, provided the particles are adequately dispersed. However, excessive addition of these particles can result in a reduction in material strength (Zidi et al., 2021).

3.2 Density Test Results

A series of density tests were conducted prior to the pressing process of the nanocomposite polymer concrete. The cubes were weighed at 28 days, and the results demonstrated that the lowest density was recorded for the mixture with a 1:1 ratio of epoxy resin and a 0.5% nano-silica addition, which was 1562.67 kg/m^3. In contrast, the mixture with a ratio of 2:1 yielded a density of 1578.67 kg/m^3. This condition occurs after the addition of nano-silica, where the more nano was used, the weight decreased, as shown in Figure 3.

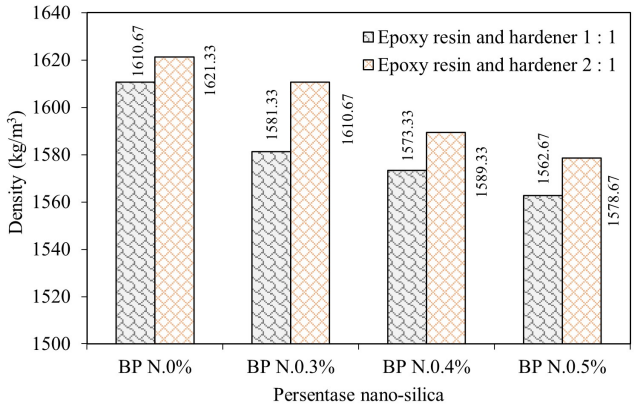

Figure 3. The Specific Gravity of Polymer Concrete Aged 28 days

A polymer density comparison was also conducted, adding epoxy resin lightweight polymer concrete (LPC) with a weight between 1300 and 1600 kg/m^3 (Hasyim et al., 2021). The density and polymer content increased until the threshold was reached (Sanaei Ataabadi et al., 2021). The nano-silica material dramatically influences the specific gravity because it has a light specific gravity and refined grains that can fill the empty cavities in the specimen (Liu et al., 2019).

The specific gravity of a polymer may undergo a decrease over time. This phenomenon is attributable to a number of factors. The hardening and drying of the polymer, which occurs due to the evaporation of volatile components or shrinkage of the material, can decrease specific gravity. Furthermore, the distribution of nano-silica particles, which have a low density, also influences this phenomenon. The greater the quantity of nano-silica employed, the lower the specific gravity of the polymer. Environmental factors, such as humidity and temperature, also impact the polymer by causing the material's expansion, contraction, or degradation, which in turn can alter its specific gravity.

3.3 Compressive Strength Test Results

Provides a framework for the investigation of the influence of silica nanoparticles on the compressive strength and durability of epoxy resin blends in a 1:1 and 2:1 ratio Figure 4. For epoxy resin blends with a 1:1 ratio devoid of silica nanoparticles (BPN 0%), the compressive strength reached 40.05 MPa. Incorporating nanoparticles with the appropriate module demonstrates a mechanism that aligns with its intended functionality. As for adding 0.3% nano-silica (BPN 0.3%), the compressive strength increased significantly to 44.81 MPa. This increase shows that adding a small amount of nano-silica can significantly reinforce the mixture. The compressive strength peaked at 45.23 MPa with the addition of 0.4% nano-silica. However, if nano-silica was added beyond this optimum percentage of 0.5%, the compressive strength decreased to 43.88 MPa, although it was still higher than without nano-silica addition.

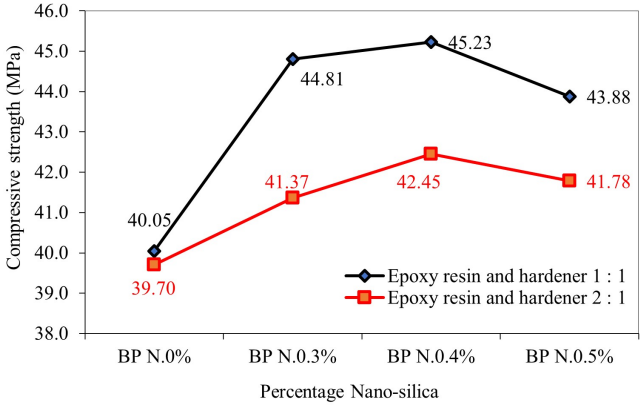

Figure 4. Compressive Strength of Polymer Concrete Aged 28 days

Meanwhile, for the epoxy resin and hardener mixture with a ratio of 2:1, the initial compressive strength without adding nano-silica (BPN 0%) was 39.70 MPa, slightly lower than the 1:1 ratio. Adding 0.3% nano-silica (BPN 0.3%) increased the compressive strength to 41.37 MPa. With the addition of 0.4% nano-silica, the compressive strength reached the highest value of 42.45 MPa. However, as in the 1:1 ratio, adding nano-silica beyond the optimum percentage decreased the compressive strength by 41.78 MPa at adding 0.5% nano-silica.

The compressive strength of the epoxy resin and hardener mixture exhibited a similar trend of increase and decrease with the addition of nano-silica. However, the compressive strength values at each percentage of nano-silica were higher for the 1:1 ratio than the 2:1 ratio. This indicates that the mix ratio between epoxy resin and hardener significantly influences compressive strength. The 1:1 ratio yielded superior compressive strength compared to the 2:1 ratio, indicating that a balanced ratio of resin and hardener results in a more robust and stress-resistant material structure. This analysis is crucial for determining the optimal formulation in practical applications of nanocomposite polymer concrete, ensuring the desired strength and durability. Therefore, adding nano-silica to the mixture can increase the strength compared to a matrix without nano-silica (Kumar et al., 2020; Septriansyah et al., 2021). This shows that adding a small amount of nano-silica can increase the compressive strength of concrete.

3.4 FT-IR Test Results

The FT-IR observations of the materials with varying matrix composition were interpreted using the correlation and comparison tables presented in Table 1. This analysis allows the identification of functional groups and chemical structure changes that occur due to variations in matrix composition. By comparing the FT-IR spectra, any change in composition affects the overall material properties.

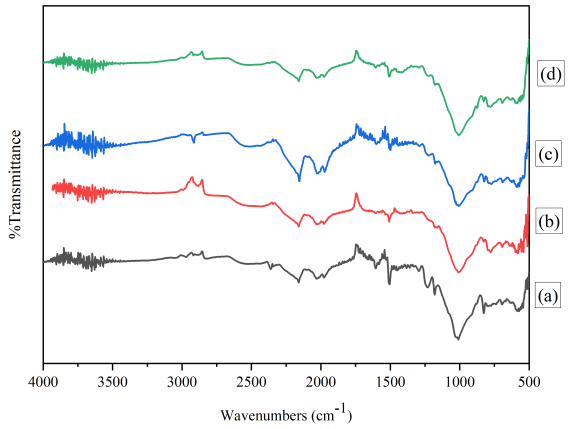

Figure 5. FT-IR Test for a Material with a Ratio of 1:1, (a) BP N.0%, (b) BP N.0.3%, (c) BP N.0.4%, and (d) BP N.0.5%

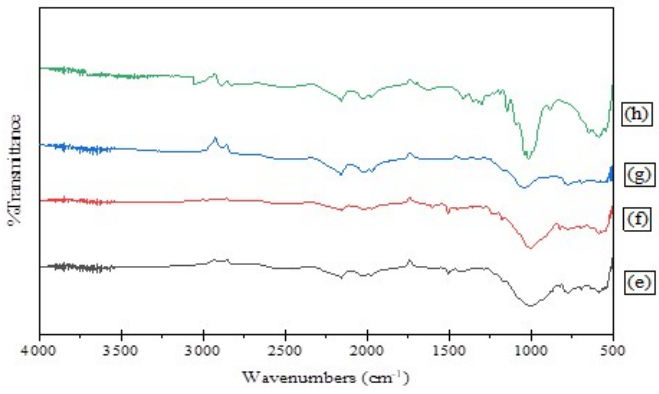

Figure 6. FT-IR Test for a Material with a Ratio of 2:1, (e) BP N.0%, (f) BP N.0.3%, (g) BP N.0.4%, and (h) BP N.0.5%.

Table 1 reveals a notable change in the polymer concrete composition with the addition of 0.4% nano-silica, which exhibits an absorption band corresponding to OH bond vibrations. This band is distinct from those observed in other poly-

Table 1. Interpretation of the FT-IR Test for a Material with a Ratio of 1:1

Vibration	BPN 0%		BPN 0.3%		BPN 0.4%		BPN 0.5%	
	V (cm^{-1})	%T	V (cm^{-1})	%T	V (cm^{-1})	%T	V (cm^{-1})	%T
O−H	-	-	3245.27	106.226	-	-	-	-
C−H	-	-	2883.62	107.697	2918.44	101.808	2514.61	99.753
C−C	2159.44	90.668	2159.53	99.655	2159.00	90.197	2159.45	92.480
CO_2	2032.01	92.437	2030.05	100.084	2029.25	92.533	2030.87	93.997
NO_2	1504.24	89.857	1508.31	100.590	1547.40	103.067	1508.40	94.538
–C−H_3 Asymmetrical	-	-	-	-	1482.86	101.253	-	-
–C−H_2 Symmetrical	-	-	-	-	1382.70	101.260	1413.33	96.289
CH_3C=C	1180.42	84.970	-	-	-	-	-	-
SiO_2	1010.17	64.070	1007.24	90.548	1009.63	82.705	1008.05	68.321
C−H	836.63	76.318	-	-	826.50	90.138	826.87	83.507
(CH_2)n	798.28	79.677	777.78	94.564	774.28	89.395	776.25	81.008

Table 2. Interpretation of the FT-IR Test for a Material with a Ratio of 2:1

Vibration	BPN 0%		BPN 0.3%		BPN 0.4%		BPN 0.5%	
	V (cm^{-1})	%T	V (cm^{-1})	%T	V (cm^{-1})	%T	V (cm^{-1})	%T
O−H	-	-	-	-	2438.55	102.409	3333.72	83.743
C−H	-	-	2514.67	101.116	-	-	2890.13	99.325
C−C	2159.93	93.397	2159.53	94.468	2159.67	90.062	2159.35	87.087
CO_2	2030.13	94.974	2032.81	95.551	2032.24	92.352	2030.31	89.404
NO_2	1507.86	96.868	1507.19	92.013	1560.00	102.074	1427.00	89.249
–C−H_3 Asymmetrical	-	-	-	-	-	-	-	-
–C−H_2 Symmetrical	1412.35	98.805	1229.58	91.608	-	-	-	-
CH_3C=C	-	-	-	-	-	-	1202.55	93.013
SiO_2	1008.51	72.009	1008.82	65.610	1049.40	80.815	1029.49	79.295
C−H	-	-	826.63	80.167	-	-	896.27	42.771
(CH_2)n	777.55	81.842	775.07	80.353	776.23	82.550	598.18	59.927

mer concrete compositions. In contrast, these latter compositions exhibit absorption bands for CH and all SiO_2 bond vibrations. The absorption bands associated with the vibrations of the SiO_2 bonds in all of the polymer concrete compositions exhibit similar wavelength and transmittance values, except the composition with 0.4% nano-silica, which demonstrates the presence of OH absorption bands.

The analysis of the polymer concrete (BP N.0%) composition revealed the presence of nine distinct chemical bond types, including CH, CC, CO_2, NO_2, −C−H_3, −C−H_2, SiO_2, twisted CH bonds, and (CH_2) bonds, when 0.4% nano-silica was added. The presence of the SiO_2 bond group can be identified by the distinctive high peak and wide gap in the graph depicted in Figure 5.

In contrast, the data in Table 2 indicate that in the composition of BPN with 0, 4% nano-silica, six distinct bond types are present: CH, CC, CO_2, NO_2, SiO_2, and (CH_2). The SiO_2 bond group in this composition is distinguished by a pronounced peak and a considerable gap width, as illustrated in Figure 6.

Infrared spectroscopic analysis revealed the presence of various functional groups in the sample. The absorption bandwidth observed between 37000-3000 cm^{-1} indicates the presence of alcohol compounds containing hydrogen-bonded hydroxyl groups. In addition, the peak found in the range of 2853-2962 cm^{-1} indicates the presence of aliphatic hydrocarbons with carbon-carbon double bonds. The absorption band observed around 2190-2260 cm^{-1} indicates the presence of compounds containing alkynes or alkynes. The region between 2000-2300 cm^{-1} shows the characteristic absorption of ester compounds with two carbon-carbon double bonds. Furthermore, the appearance of peaks attributed to nitro groups indicates the presence of nitrogen-containing compounds, as reported in the literature (Kumar et al., 2020). It has been demonstrated that incorporating nanoscale silica (SiO_2) particles can modify the bonding properties of nanocomposite materials (Suanto et al., 2022).

The FTIR spectra of polymer concrete modified with nano silica exhibited a shift in the wave number of the Si−O vibration. This phenomenon was observed at two distinct mixing ratios between epoxy resin and hardener, specifically 1:1 and 2:1.

At a ratio of 1:1, a shift in the Si−O vibration was observed, with a decrease in the wave number. This shift indicates a

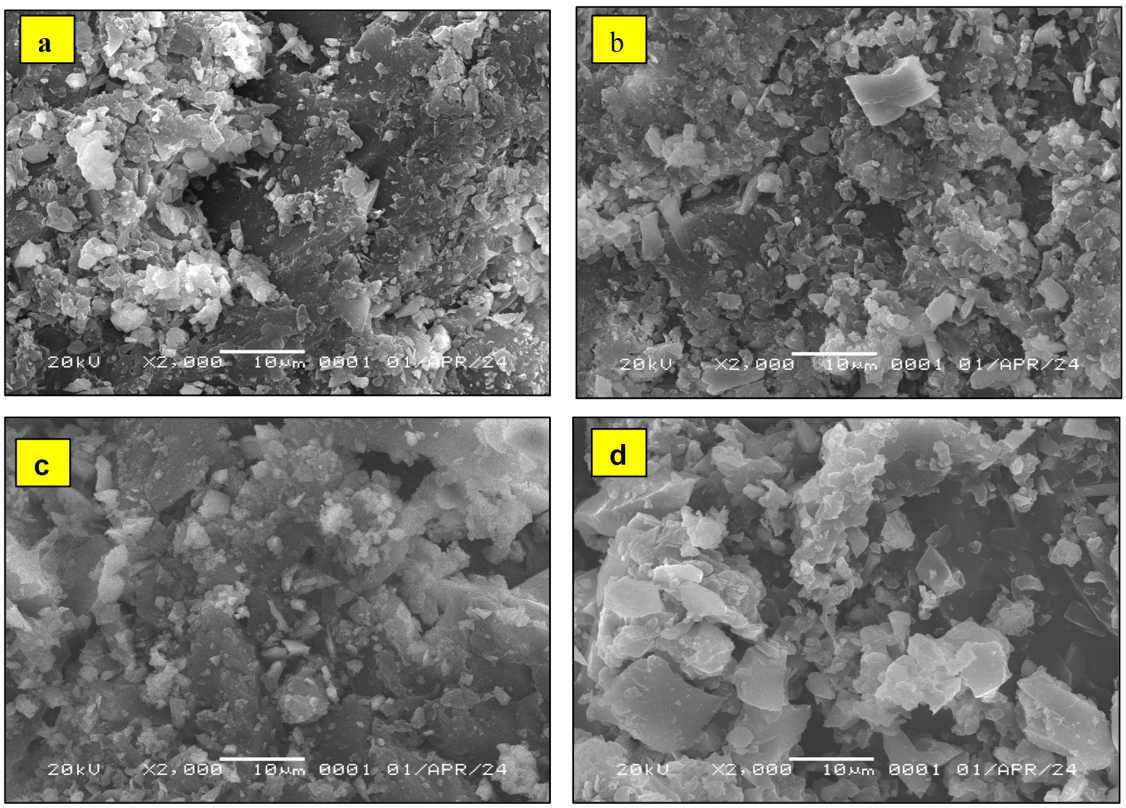

Figure 7. Surface Morphological of (a) BPN 0%, (b) BPN 0.3%, (c) BPN 0.4%, and (d) BPN.0.5%

change in the chemical environment of the Si−O bond, which is caused by the interaction between nano silica and the polymer matrix. Specifically, this interaction will likely reduce the strength of the Si−O bond or alterations to its electronic environment. When nano silica is dispersed in epoxy resin at this ratio, the nano silica particles may interact more strongly with the newly formed polymer network, resulting in a decrease in wave numbers, as observed in the FTIR spectra.

In contrast, at a 2:1 ratio, the Si−O vibrational wave number reverts to a value nearly identical to its initial value. This suggests that at this ratio, the chemical structure of the formed polymer network is more stable and less affected by the presence of nano silica compared to the 1:1 ratio. At a 2:1 ratio, the interaction between the nano-silica particles and the polymer matrix is likely insufficient to cause a significant shift in the wave number, resulting in minimal change to the Si−O vibrations.

The findings of this analysis demonstrate that alterations in the ratio of epoxy resin to hardener have a considerable influence on the molecular interactions within the composite system. The shifts in wave number observed in the FTIR spectra suggest alterations in the chemical environment and structure of the polymer network formed, contingent on the mixing ratio.

In conclusion, these results demonstrate the significance of optimizing the mixing ratio in formulating polymer-nano silica composites to achieve the desired material properties. A ratio of 1:1 indicates a more vital interaction between the nano silica and the polymer matrix, which may be beneficial in applications where increased mechanical strength or modification of the material's physical properties is required. In contrast, a ratio of 2:1 may be more suitable for applications where chemical structure stability and retention of the original properties of the polymer component are favoured.

3.5 SEM Test Results

Show that nano-silica nanoparticles can effectively fill the void in the specimen. The distribution of fumed silica nanoparticles is significantly proportional to the composition of the mixture. In addition, some cracks are caused by the cross-reaction between epoxy resin and curing. Figure 7(a) shows that BPN0% has many micro-cracks and forms irregular angles characterized by clumps. The particle size of BPN0% is mainly in the range of 10-30 μm (Figure 8(a)), indicating a high proportion of fine particles, which may affect the compressive strength of the specimen. In contrast, BPN0.3% (Figure 7(b)) appears to have grains of different shapes and are denser. The particle size distribution shown in Figure 8(b) mainly decreased around 10 μm by adding nano silica up to 0.3% by weight of epoxy resin. Meanwhile, Figure 7(c). BPN0.4% grains show a tighter and more composite shape; this causes an increase in the compressive strength of concrete specimens observed when

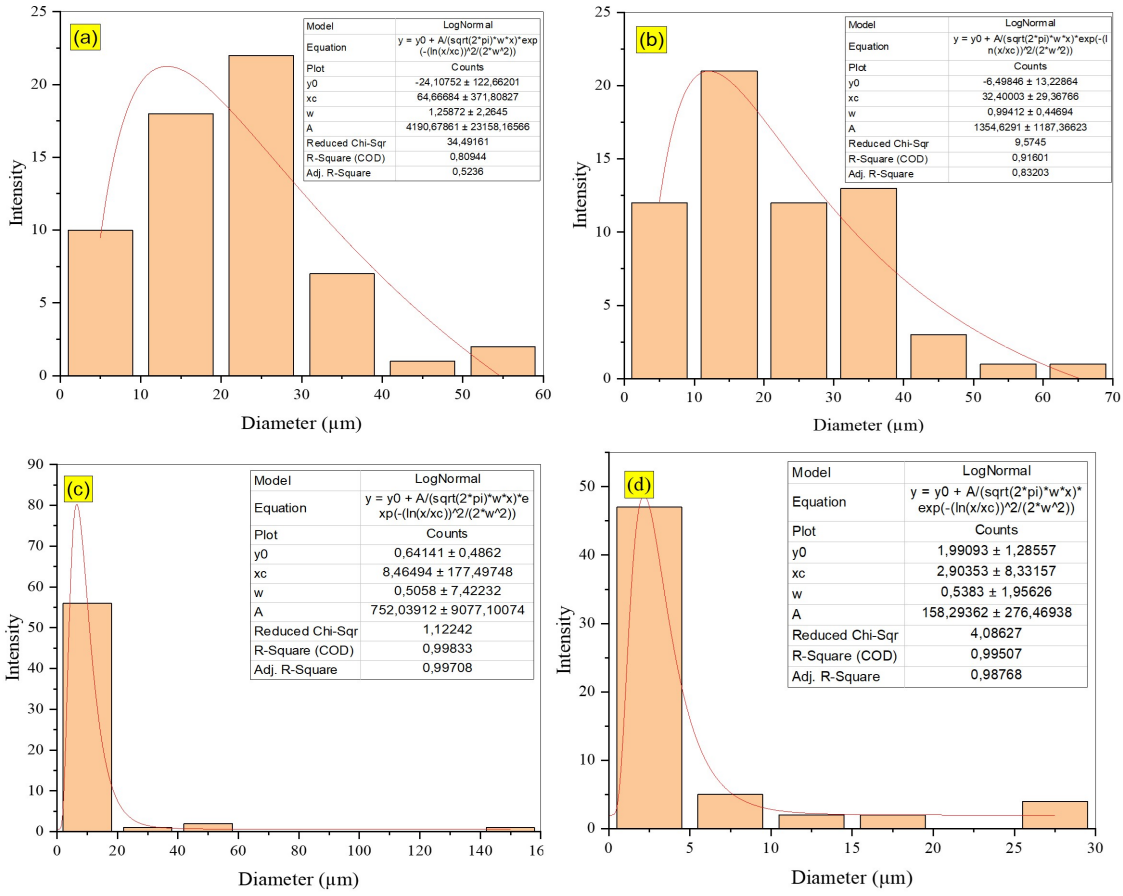

Figure 8. Particle Size Distribution of (a) BPN 0%, (b) BPN 0.3%, (c) BPN 0.4%, and (d) BPN.0.5%

the concentration of nano silica reaches a peak of 0.4% with a particle size distribution of 0-20 μm shown in Figure 8(c). However, as the nano-silica content increases, the compressive strength of the concrete gradually decreases.

Nanocomposites profoundly influence the properties of homogeneous materials, resulting in enhanced strength (Liou and Liou, 2021; Prasad et al., 2019). Applying suitable processing techniques makes it possible to alter the surface of nanoparticles, thereby facilitating their dispersion (Abhilash et al., 2021; Ahmed et al., 2022; Septriansyah et al., 2021). This enables nanoparticles to occupy molecular voids and to provide a more robust network structure when combined with a mixture of nano-SiO_2 and epoxy resin (Garg et al., 2020; Liu et al., 2021). The judicious application of processing techniques ensures that nanoparticles are evenly distributed and that the empty gaps are filled, thereby improving the overall strength and properties of the material.

The particle size distribution analysis of the four SEM images demonstrates that incorporating nano-silica has a pronounced impact on the dimensions, morphology, and complexity of the particles within the composite material. The incorporation of nano silica results in an increase in the average particle size and a transformation in the particle morphology from a more rounded and smaller shape to a larger, elongated, and complex one. While this may enhance the mechanical properties of the composite material, such as strength and elastic modulus, the non-uniform distribution and augmented complexity of the particle shape may also introduce potential weak points in the material that necessitate attention in practical applications.

3.6 X-Ray Diffraction (XRD) Testing of Composite Materials

XRD testing was carried out on two samples with different material compositions. The first sample was taken from a specimen without nano-silica with a compressive strength of 40.05 MPa. In comparison, the second sample was taken from a specimen with nano-silica with the highest compressive strength of 45.23 MPa. The test results showed that the identified phase in the sample without nano-silica was silica in the sand with a triclinic crystal structure. In contrast, the sample with the addition of nano-silica exhibited a hexagonal structure. This indicates that nano-silica silica used in the specimen composition was amorphous and mixed with epoxy resin and hardener (Shilar et al., 2022).

For the sample without nano-silica, the silica crystal lattice

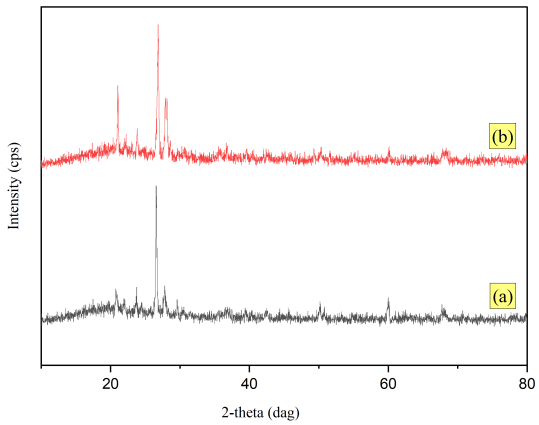

Figure 9. XRD Test Results (a) BPN 0% and (b) BPN 0.4%

parameters were a = b = 4.911 Å, c = 5.406 Å, $\alpha = \beta = 90^{\circ}$, $\gamma = 120.01^{\circ}$. The crystallite size was 303.5 Å, with a lattice strain of 0.19% (Figure 9). Meanwhile, in the sample with the addition-silica silica, the SiO_2 crystal lattice parameters were slightly different, namely 4.873 Å, c = 5.378 Å, $\alpha = \beta = 90^{\circ}$, $\gamma = 120^{\circ}$. The SiO_2 crystallite size in this sample was more significant, at 505 Å, with a higher lattice strain of 0.49.

This finding can be inferred that differences in crystal lattice parameters, crystal size, and lattice strain between the two samples may contribute to the observed difference in compressive strength possessed by specimens without nano silica and specimens with nano silica. The larger nano-sized SiO_2 crystal size and higher lattice strain in specimens with nano-silica may affect the material's mechanical properties, such as higher compressive strength, than in specimens without nano-silica (Wirayudha et al., 2023).

4. CONCLUSIONS

Based on the data analysis results, adding nano-silica to the polymer concrete mixture positively impacts the mechanical characteristics of concrete. The optimal composition was found in a mixture of epoxy resin and hardener 1:1 and the addition of 0.4% nano-silica, which produced a maximum compressive strength of 45.23 MPa with a specific gravity of 1573.33 kg/m^3. This shows a significant increase compared to concrete without nano-silica. The results of XRD testing revealed that the nano-silica used had a high amorphous phase and a hexagonal structure, contributing to the increase in concrete strength. SEM analysis showed an effective distribution of nano-silica particles in the concrete matrix, increasing the density and strength of the concrete. Meanwhile, the FT-IR results confirmed the presence of SiO2 bonds in the polymer concrete mixture containing nano-silica, which played a role in increasing the strength of the concrete. This study shows that using nano-silica in polymer concrete can produce a promising alternative material construction with superior mechanical properties, especially regarding compressive strength and density.

5. ACKNOWLEDGEMENT

The authors thank the Department of Civil Engineering, Faculty of Engineering, Sriwijaya University, for providing the necessary facilities and support for this research. We would also like to thank the instructors in the laboratory who have assisted with its implementation.

REFERENCES

Abhilash, P. P., D. K. Nayak, B. Sangoju, R. Kumar, and V. Kumar (2021). Effect of Nano-Silica in Concrete: A Review. *Construction and Building Materials*, **278**; 122347

Ahmed, H. U., A. A. Mohammed, and A. S. Mohammed (2022). The Role of Nanomaterials in Geopolymer Concrete Composites: A State-of-the-Art Review. *Journal of Building Engineering*, **49**; 104062

Bautista-Gutierrez, K. P., A. L. Herrera-May, J. M. Santamaría-López, A. Honorato-Moreno, and S. A. Zamora-Castro (2019). Recent Progress in Nanomaterials for Modern Concrete Infrastructure: Advantages and Challenges. *Materials*, **12**(21); 1–40

Chauhan, K. and R. K. Tiwari (2020). Study of Thermomechanical Properties of Glycidoxypropyl Trimethoxy Silane Functionalized Nanosilica/Amine Terminated Poly (Butadiene-Co-Acrylonitrile) Rubber Modified Novolac Epoxy Composites for High Performance Applications. *Journal of Polymer Research*, **27**(10)

Ferdous, W., A. Manalo, H. S. Wong, R. Abousnina, O. S. AlAjarmeh, Y. Zhuge, and P. Schubel (2020). Optimal Design for Epoxy Polymer Concrete Based on Mechanical Properties and Durability Aspects. *Construction and Building Materials*, **232**; 117229

Firda, A., A. Saggaff, Hanafiah, and Saloma (2023). Characteristic of Polymeric Lightweight Aggregate with Coal Fly Ash and Epoxy Resin for Manufacturing the Lightweight Concrete. *Civil Engineering and Architecture*, **11**(1); 473–485

Garg, R., R. Garg, M. Bansal, and Y. Aggarwal (2020). Experimental Study on Strength and Microstructure of Mortar in Presence of Micro and Nano-Silica. *Materials Today: Proceedings*, **43**; 769–777

Hasyim, S., S. A. Nurjannah, A. P. Usman, F. S. Putra, and M. F. A. Hashim (2021). The Durability of Lightweight Concrete Against 5% Hydrochloric Acid Solution with Various Size of Expanded Polystyrene. *AIP Conference Proceedings*, **2347**; 1–10

Huseien, G. F., K. W. Shah, and A. R. M. Sam (2019). Sustainability of Nanomaterials Based Self-Healing Concrete: An All-Inclusive Insight. *Journal of Building Engineering*, **23**; 155–171

Ismail, A., I. Akbar Alamsyah, M. Kholil, B. Heru Susanto, and M. Nasikin (2018). The Effect of Milling Time on the Size of Silica Particles from Silica Sand. In *Materials Science*

Forum, volume 917. Trans Tech Publications Ltd., pages 162–166

Khan, K., W. Ahmad, M. N. Amin, and S. Nazar (2022). Nano-Silica-Modified Concrete: A Bibliographic Analysis and Comprehensive Review of Material Properties. *Nanomaterials*, **12**(12)

Kiruthika, C., S. Lavanya Prabha, and M. Neelamegam (2020). Different Aspects of Polyester Polymer Concrete for Sustainable Construction. *Materials Today: Proceedings*, **43**; 1622–1625

Kumar, S., Sirajudeen, V. Sivaranjani, N. Ali, S. Begum, and Z. Rahman (2020). Characterization, Properties and Microstructure Studies of Cement Mortar Incorporating Nano-SiO_2. *Materials Today: Proceedings*, **37**; 425–430

Lamm, M., Z. Wang, J. Zhou, L. Yuan, X. Zhang, and C. Tang (2018). Sustainable Epoxy Resins Derived from Plant Oils with Thermo- and Chemo-Responsive Shape Memory Behavior. *Polymer*, **144**; 121–127

Liang, X., W. Bao, and Y. Gao (2018). Decay-Like Fracture Mechanism of Silicone Rubber Composite Insulator. *IEEE Transactions on Dielectrics and Electrical Insulation*, **25**(1); 110–119

Linec, M. and B. Music (2019). The Effects of Silica-Based Fillers on the Properties of Epoxy Molding Compounds. *Materials*, **12**(11); 1–11

Liou, T. and Y. Liou (2021). Utilization of Rice Husk Ash in the Preparation of Graphene-Oxide-Based Mesoporous Nanocomposites with Excellent Adsorption Performance. *Materials*, **14**(5); 1–21

Liu, M., H. Tan, and X. He (2019). Effects of Nano-SiO_2 on Early Strength and Microstructure of Steam-Cured High Volume Fly Ash Cement System. *Construction and Building Materials*, **194**; 350–359

Liu, Y., Z. Liang, J. Liang, and L. Liao (2021). Effect of Different Surface Properties of Nanosilica on Retrogradation Behavior and Structures of Thermoplastic Cassava Starch. *Journal of Polymer Research*, **28**(5)

Ma, H., X. Zhang, F. Ju, and S. Tsai (2018). A Study on Curing Kinetics of Nano-Phase Modified Epoxy Resin. *Scientific Reports*, **8**(1); 1–16

Prasad, T., S. Halder, and S. Dhar (2019). Imidazole-Supported Silica One-Pot Processed Nanoparticles to Enhance Toughness of Epoxy Based Nanocomposites. *Materials Chemistry and Physics*, **231**; 75–86

Sanaei Ataabadi, H., A. Zare, H. Rahmani, A. Sedaghatdoost, and E. Mirzaei (2021). Lightweight Dense Polymer Concrete Exposed to Chemical Condition and Various Temperatures: An Experimental Investigation. *Journal of Building Engineering*, **34**; 101878

Septriansyah, V., A. Saggaff, and Saloma (2021). Characteristics of Nanocomposite Polymer with Temperature Variation and Heating Time by Using Simple Mixing Method. *International Journal of Advanced Technology and Engineering Exploration*, **8**(78); 651–661

Shameem, M., S. Sasikanth, R. Annamalai, and R. Raman (2021). A Brief Review on Polymer Nanocomposites and Its Applications. *Materials Today: Proceedings*, **45**; 2536–2539

Shilar, F., S. Ganachari, V. Patil, T. Khan, N. Almakayeel, and S. Alghamdi (2022). Review on the Relationship Between Nano Modifications of Geopolymer Concrete and Their Structural Characteristics. *Polymers*, **14**(7)

Singh, N. (2020). Properties of Cementitious Systems in Presence of Nanomaterials. *Materials Today: Proceedings*, **29**; 1143–1149

Suanto, P., Saloma, A. Usman, A. Saggaff, M. Ismail, and N. Khalid (2022). The Characterization of Nanocellulose with Various Durations and NaOH Concentration. *International Journal of Innovative Research and Scientific Studies*, **5**(1); 18–29

Wirayudha, M., Saloma, A. Saggaff, A. Usman, M. Tahir, and N. Khalid (2023). The Polymer Nanocomposite Characteristics on Various Mixtures and Mixing Times in Simple Mixing Method. *Engineering Solid Mechanics*, **11**(2); 205–216

Zidi, Z., M. Ltifi, and I. Zafar (2021). Comparative Study: Nanosilica, Nanoalumina, and Nanozinc Oxide Addition on the Properties of Localized Geopolymer. *Journal of the Australian Ceramic Society*, **57**(3); 783–792

