

The Influence of Carbon Nanotubes and Nano-Silica Fume on Enhancing the Damping and Mechanical Properties of Cement-Based Materials

Bin Liu^{1,2*}, Norhaiza Nordin², Jiyang Wang³, Jingwei Wu³, Xiuliang Liu³

¹Department of Construction Engineering, Zhejiang College of Construction, Hangzhou, China

²Faculty of Engineering, Science and Technology, Infrastructure University Kuala Lumpur, Kajang, Malaysia

³College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China

Email: *82889487@qq.com

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Abstract

This paper conducted experimental studies on the damping and mechanical properties of carbon nanotube-nanosilica-cement composite materials with different carbon nanotube contents. The damping and mechanical properties enhancement mechanisms were analyzed and compared through the porosity structure test, XRD analysis, and scanning electron microscope observation. The results show that the introduction of nanosilica significantly improves the dispersion of carbon nanotubes in the cement matrix. At the same time, the addition of nanosilica not only effectively reduces the critical pore size and average pore size of the cement composite material, but also exhibits good synergistic effects with carbon nanotubes, which can significantly optimize the pore structure. Finally, a rationalization suggestion for the co-doping of nanosilica and carbon nanotubes was given to achieve a significant increase in the flexural strength, compressive strength and loss factor of cement-based materials.

Keywords

Cement-based Composites, Carbon Nanotubes, Nano Silica Fume, Damping Property, Mechanical Property

1. Introduction

Cement-based materials play a crucial role as a building material due to their easy availability of raw materials, convenient preparation, good durability, and high

cost-effectiveness. This has led to their widespread use across different engineering fields. The increasing demand for high-rise, large-scale, and large space buildings. In order to meet this demand, research on achieving large-span by improving the high performance of building materials is also steadily advancing [1]. Consequently, higher requirements for the dynamic properties of concrete structures have emerged and the control of structure vibrations has become increasingly important. Effective vibration control not only extends the service life of structures but also reduces maintenance costs, minimizes noise pollution and enhances the overall comfort level of structures [2].

Carbon nanotubes have excellent mechanical, thermal, optical, and electrical properties, making them a trending subject in the area of cement-based composite materials [3]-[5]. In recent years, scholars from both within the country and abroad have incorporated carbon nanotubes into cement to improve the mechanical and damping properties of cement-based composite materials. Carbon nanotubes offer a significant advantage in enhancing mechanical properties, even with minimal addition [6]. Previous studies [7]-[10] have demonstrated that incorporating CNTs can lead to increased compressive strength, tensile strength, and modulus of elasticity, primarily due to the bridging effect. Moreover, by incorporating an optimal amount of CNTs, the mechanical properties of cement composites can be further enhanced by improving the properties of the interfacial transition zone (ITZ) [11]. Aside from these, CNTs also contribute to enhanced electrical conductivity and provide electromagnetic wave shielding effects [12] [13].

Nano-silica, a material with nanometer-scale dimensions, has attracted considerable interest due to its remarkable reactivity, extensive surface area, and fine particle size [14]. Its properties as a pozzolanic agent, nucleating agent, and filler enhance its utility in concrete production. Nano-silica accelerates cement hydration, resulting in increased strength, which is particularly advantageous for concrete applications [15]. Jalal *et al.* [16] found that adding silica fume (SF) to self-consolidating concrete not only enhances mechanical properties and electrical resistivity but also reduces water absorption. The incorporation of SF also mitigates chloride ion penetration and lowers the likelihood of segregation and bleeding. By improving the interaction between cementitious materials and creating a denser microstructure, SF significantly boosts concrete strength due to its high surface area and pozzolanic characteristics [17].

Liew *et al.* studied the damping performance of cement mortar reinforced by carbon nanotubes and found that the dissipation factor could be increased by 25.9% after TNWDIS-dispersed carbon nanotubes were used. And the damping performance of cement-based composite materials reinforced by carbon nanotubes mainly comes from the physical and chemical adhesion and mechanical interlock between carbon nanotubes and the cement matrix [18]. Luo *et al.* tested the damping performance of cement-based composite materials reinforced by silica fume and carbon nanotubes using the free decay method, half-power bandwidth method, and three-point bending method, and found that carbon nanotubes

can improve the damping ratio of the composite material by 30% by dissipating energy through friction with the cement matrix [19]. Koratkar *et al.* studied the damping of single walled carbon nanotubes (SWCNTs) and found that the improvement in composite material damping mainly comes from the sliding energy dissipation at the interface between the carbon nanotubes and the matrix, rather than the sliding energy dissipation between the inner walls of the carbon nanotubes [20]. Despite the fact that carbon nanotubes can substantially improve the damping properties of cement-based materials, research has found that effective dispersed carbon nanotube dispersions tend to re-aggregate in fresh cement matrix during mixing with cement, forming large-sized carbon nanotube agglomerates with internal voids, with only a small fraction of the carbon nanotubes being anchored in the cement matrix, while most of them only serve to fill pores and cracks and have not effectively bonded with the cement matrix [21].

In order to further improve the damping and the mechanical characteristics of cement-based composites reinforced with carbon nanotubes, improving the dispersion of carbon nanotubes in the cement matrix is crucial. Silica fume, a commonly used pozzolanic material in cement-based materials, can effectively solve the above problem. The size of nanoscale silica fume is between 10-500 nm, similar in size to carbon nanotubes, thus it can effectively mix with agglomerated carbon nanotubes and physically disperse the agglomerated carbon nanotube bundles into dispersed carbon nanotubes during mixing. Kim *et al.* enhanced the distribution of carbon nanotubes by incorporating silica fume as a dispersing agent under mechanical stirring. This approach led to further improvements in both the mechanical and electrical properties of the carbon nanotube-reinforced cement composite [8] [22]. Yazdanbakhsh *et al.* studied that silica fume can mechanically disperse carbon nanofibers and effectively prevent the re-agglomeration of carbon nanofibers in the cement matrix [23]. Moreover, silica fume, due to its strong pozzolanic activity, hydrates with the carbon nanotubes added, effectively anchors the carbon nanotubes, and enhances the interfacial interaction between the carbon nanotubes and the hydration products [24].

Therefore, this study takes this as a starting point to study the mechanical and damping properties of 17 different carbon nanotube silica fume cement composites of different carbon nanotube contents, while using microscopic techniques to provide a multi-angle explanation of the impacts of silica fume and carbon nanotubes on the cement matrix and to elucidate their mechanisms of action. Meanwhile, this study can provide a reasonable ratio recommendation for carbon nanotubes and nanoscale silica fume to enable cement-based materials to achieve optimal mechanical and damping properties.

2. Test Materials and Methods

2.1. Test Raw Materials

The test raw materials include ordinary Portland cement, carbon nanotubes, surfactant TNWDIS, nanometer silica fume dispersion liquid, and water. The cement

used is P.O 42.5 cement, and the test water is distilled water. The performance of the carbon nanotube material is shown in **Table 1**, and the concentration of the nanometer silica fume water-based dispersion liquid is 25%.

Table 1. Property of MWCNTs.

Material	Outer Diameter (nm)	Purity (wt.%)	Length (μm)	Specific Surface Area ($\text{m}^2\cdot\text{g}^{-1}$)	Ash Content (wt.%)	Bulk Density ($\text{g}\cdot\text{cm}^{-3}$)
Multi-Walled Carbon Nanotubes	30 - 80	>98	<10	>60	<1.5	0.18

2.2. Preparation of Carbon Nanotube Pre-Dispersion Solution

Due to the extensive surface area of carbon nanotubes, strong intermolecular forces and electrostatic attraction, they often agglomerate into large-sized agglomerates. This makes it difficult to uniformly disperse untreated carbon nanotubes in cement matrix. If large agglomerates of carbon nanotubes appear in the cement matrix on a large scale, it is equivalent to introducing pores and defects into the cement matrix. This not only affects the carbon nanotubes from fully utilizing their own excellent properties, but may even have a negative impact on the overall performance of the composite material.

In this experiment, a stable carbon nanotube pre-dispersion solution was obtained by using surfactant TNWDIS and ultrasonic treatment. The molecular structure of nonionic surfactant TNWDIS consists of a long carbon chain connected to an aromatic ring and a hydrophilic group. In the process of achieving uniform dispersion, the aromatic ring can firmly adsorb the carbon nanotube, and the hydrophilic group can effectively improve the dispersibility of the carbon nanotube in water.

The preparation process of carbon nanotube pre-dispersed liquid is as follows:

- 1) Add 4 g TNWDIS to 180 g deionized water.
- 2) Add 20 g of carbon nanotubes and stir evenly with a glass stirring rod.
- 3) Perform ultrasonic treatment, with each stage of ultrasonic treatment lasting 5 minutes, and repeat the ultrasonic operation 6 times, with a cumulative ultrasonic time of 30 minutes.
- 4) Perform centrifugation, with a centrifugation speed of 2000rpm and a centrifugation time of 30 minutes.
- 5) Pass the centrifuged upper layer liquid through a 300-mesh filter cloth to obtain a carbon nanotube pre-dispersed liquid that meets the requirements.

2.3. Preparation of Carbon Nanotube Cement-Based Composites

This experiment designed 17 carbon nanotube-nanosilica-cement-based composite materials accompanied by different carbon nanotube contents. The water-to-cement ratio was set to 0.35. **Table 2** details the specifications and proportions of the various mixtures. The specimens were prepared and cured according to the

“Test Methods for Cement and Concrete Used in Highway Engineering” (JTG 3420-2020) [25]. For each mixture, three specimens were made for mechanical properties testing and six specimens were made for damping properties testing.

First, mix the supplementary water and carbon nanotube dispersion liquid and stir at high speed (280rpm) for 1 minute; then, add the nanoscale silica fume dispersion liquid and stir at low speed (140rpm) for 1 minute. Finally, add the measured cement and stir at low speed (140rpm) for 3 minutes, then at high speed (280rpm) for 2 minutes. After that, pour the mixture into the mold and vibrate it using a high-frequency vibration table for 30 seconds to remove the bubbles generated during the casting process. Then, wrap the specimen with a plastic film and keep it for 24 hours to prevent water loss. After demolding, all specimens were stored in a curing chamber set at $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ with 95% relative humidity for a duration of 28 days.

Table 2. Mix proportions of cement based materials enhanced with carbon nanotubes and nano silica fume.

Number	Cement (g)	Total water (g)	Silica fume concentration (%)	Silica fume (g)	Silica fume solution (g)	Water in Silica Fume Solution (g)	Carbon Nanotubes (g)	Carbon nanotube concentration (%)	Carbon Nanotube Solution (g)	Water in Carbon Nanotube Solution (g)
NS0 CNT000							0	0	0	0
NS0 CNT005							0.75	0.05	7.5	6.75
NS0 CNT010	1500	525	0	0	0	0	1.5	0.10	15	13.5
NS0 CNT020							3	0.20	30	27
NS0 CNT030							4.5	0.30	45	40.5
NS25 CNT005							0.75	0.05	7.5	6.75
NS25 CNT010	1500	525	2.5	37.5	150	112.5	1.5	0.10	15	13.5
NS25 CNT020							3	0.20	30	27
NS25 CNT030							4.5	0.30	45	40.5
NS50 CNT005							0.75	0.05	7.5	6.75
NS50 CNT010	1500	525	5	75	300	225	1.5	0.10	15	13.5
NS50 CNT020							3	0.20	30	27
NS50 CNT030							4.5	0.30	45	40.5
NS75 CNT005							0.75	0.05	7.5	6.75
NS75 CNT010	1500	525	7.5	112.5	450	337.5	1.5	0.10	15	13.5
NS75 CNT020							3	0.20	30	27
NS75 CNT030							4.5	0.30	45	40.5

2.4. Test Methods

Mechanical property testing: The mechanical property testing equipment used is an Instron high-performance fatigue testing machine (as shown in **Figure 1**). The loading rates for the bending and compression tests are 50 N/s and 2400 N/s,

Separately. The sample size is 40 mm × 40 mm × 160 mm. The flexural strength is first determined by the center loading method, and then the compression test is immediately conducted on the two broken pieces after the flexural test.

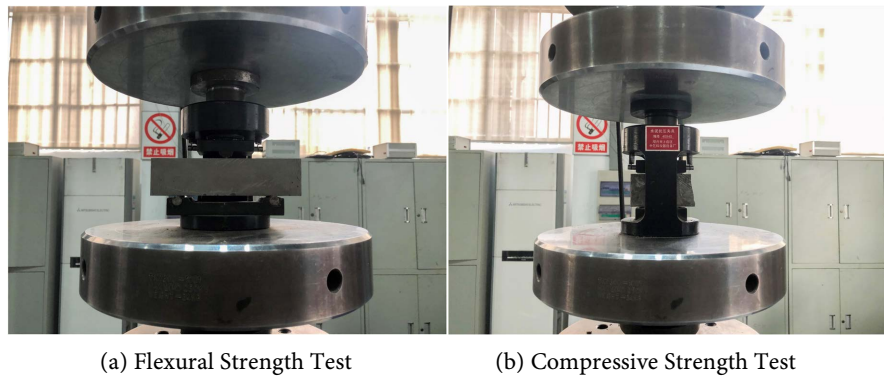


Figure 1. Equipment for flexural and compressive strength tests.

Damping performance test: The instrument used is a dynamic mechanical analyzer (DMA), which can obtain the dynamic mechanical properties of materials with respect to temperature, frequency, time, and stress under programmed temperature conditions. By applying a predetermined amplitude sinusoidal alternating stress (σ) to a known-sized sample (2.5 mm × 8 mm × 60 mm), a sinusoidal strain (ε) will be produced. The strain response of viscoelastic materials will be delayed by a certain phase difference δ . Based on the size of the phase difference δ , viscoelastic materials can be divided into three categories:

- 1) ideal elastic materials characterized by a phase angle of 0° .
- 2) ideal viscous materials characterized by a phase angle of 45° .
- 3) viscoelastic materials characterized by a phase angle between 0° and 45° .

The larger the phase difference of the material, the greater its damping.

According to equations (1) to (6), the composite modulus (M^*), storage modulus (E'), loss modulus (E'') and loss factor ($\tan \delta$) of the specimen can be calculated.

$$\varepsilon = \varepsilon_0 \sin \omega t \quad (1)$$

$$\sigma = \sigma_0 \sin(\omega t + \delta) \quad (2)$$

$$M^* = \sigma_0 / \varepsilon_0 \quad (3)$$

$$E' = \sigma_0 \cos \delta / \varepsilon_0 \quad (4)$$

$$E'' = \sigma_0 \sin \delta / \varepsilon_0 \quad (5)$$

$$\tan \delta = E'' / E' \quad (6)$$

In the equation:

ω —angular frequency.

δ —phase difference.

t —time.

ε_0 —peak strain.

σ_0 —peak stress.

M^* —The composite modulus, which refers to the ratio of the stress peak value σ_0 to the strain peak value ε_0 .

E' —Storage modulus, which measures the elastic component of the viscoelastic deformation of the material.

E'' —The loss modulus, which measures the viscous component of the material's viscoelastic response.

$\tan \delta$ —The loss factor (E'' / E') is the ratio of viscosity to elasticity.

Higher loss factor means more energy dissipation, and the loss factor is independent of the specimen size.

Pore structure test: Before conducting the pore structure test, the intact portion of the specimen obtained from the mechanical test needs to be placed in a 60°C oven for 24 hours to dry. In this study, the Autopore IV 9510 was used to measure the porosity, pore specific surface area, and pore size distribution of the cement-based composite materials. During the test, the contact angle of mercury was 130°, and the surface tension of mercury was adjusted to 485 N/m. The mercury pressure was increased from 3.7 kPa to 414 MPa, and the balance time for entering and exiting mercury was set to 10 seconds each time.

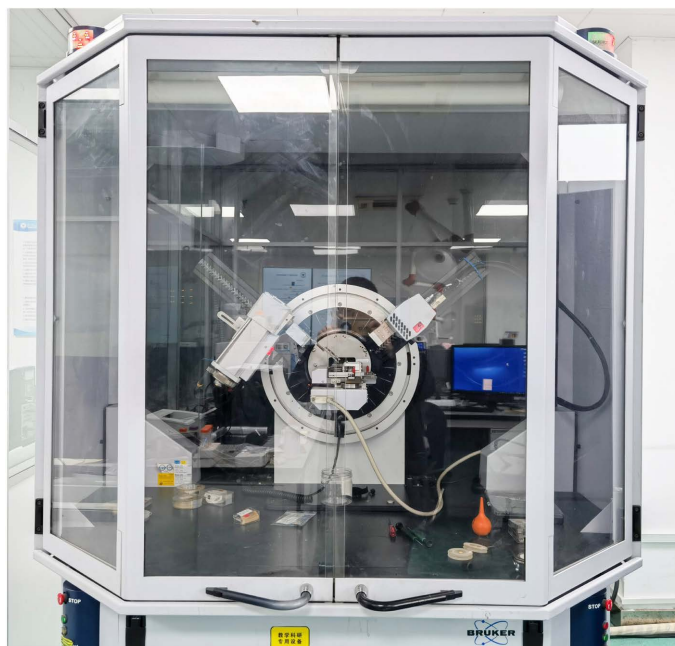


Figure 2. X-ray diffractometer: Panalytical Empyrean.

Microscopic morphological observation: Before conducting the scanning electron microscope test, the partially crushed samples that have been tested for compressive strength need to be placed in ethanol to stop hydration. Then, the samples are placed in a 60°C oven for 24 hours to dry. After drying, the samples need to be further cut to the appropriate size and glued to a conductive adhesive, which is then gold-plated. The samples are then observed.

XRD Analysis: The experimental instrument used was the Netherlands-based

Panalytical Empyrean (as shown in **Figure 2**). Before conducting the XRD test, the sample must be hydrated and dried, and then ground into powder smaller than 80 μm in size. During the test, the sample powder is placed in a sample holder and pressed flat with a glass plate. Then, the sample holder is placed on the sample holder on the detector center for scanning, with the scanning angle ranging from 10° to 80° .

3. Analysis of Test Results

3.1. Microscopic Morphology

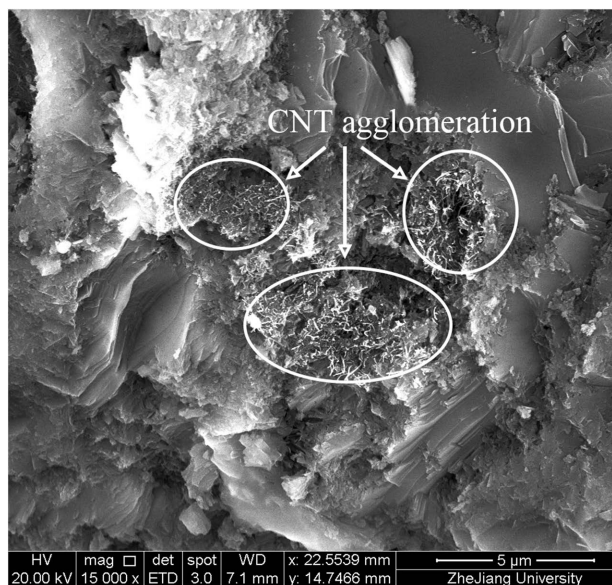


Figure 3. SEM images of cement composites of CNTs (28 day-curing).

It shows the SEM images (as shown in **Figure 3**), which indicate that for the carbon nanotube cement-based composite without silica fume, large-sized carbon nanotube agglomerates are easily observable in the SEM images, and there are a lot of pores within the agglomerates. The research results show that cement particles cannot effectively disperse carbon nanotubes, and no matter how much carbon nanotube is added, some of the carbon nanotubes tend to agglomerate again during mixing, forming large-sized carbon nanotube agglomerates with internal voids in the fresh cement matrix.

As shown in **Figure 4**, it can be observed that the presence of nano-silica particles has a significant impact on the dispersion of carbon nanotubes in the cement matrix. At the 1day age, since the cement hydration products at this time are not sufficient to cover the carbon nanotubes, and a large number of nano-silica particles have not yet hydrated, it is simple to observe a substantial amount of spherical nano-silica particles mixed with single dispersed carbon nanotubes on the surface of early hydration products. This is caused by the mechanical dispersion of nano-silica particles on carbon nanotubes during mixing. Sanchez *et al.* also found this in their study [24]. The mechanical dispersion of nano-silica on carbon nanotubes

can effectively reduce the size of carbon nanotube agglomerates [21], while filling the internal voids of carbon nanotube agglomerates in the later hydration process, improving the interfacial action between carbon nanotubes and the matrix.

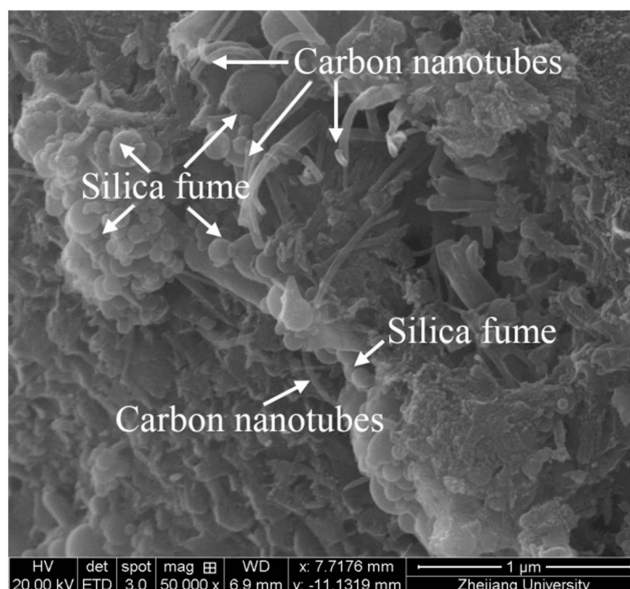


Figure 4. DMA instrument SEM images of carbon nanotube-nanosilica-cementitious composite at 1-day age (NS50 CNT0.10).

3.2. Analysis of X-Ray Diffraction (XRD)

XRD is a commonly used method for qualitative analysis of the mineral composition of the sample being tested. The relative intensity of the phase diffraction intensity peaks increases with the growth of the relative content. Due to the small sample size of typically mg for phase analysis experiments and the effects of sample absorption, the diffraction peak intensity may fluctuate, but the relative strength of the diffraction peaks can still be used as a basis for judging the relative content of the phases.

The diffraction intensity of carbon nanotube cement-based composite materials with different amounts of silica fume is shown in **Figure 5**. The diffraction results show that the peak value of CH (hydrated calcium hydroxide) decreases as the amount of silica fume increases. This is primarily because of the increase in the amount of silica fume, which leads to a reduction in the amount of cement, and thus the generation of CH is reduced. At the same time, the silica fume added will react with the CH to consume CH. It is evident that the maximum value of CH decreases most obviously when 5% silica fume is added. When the amount of silica fume is increased to 10% and 15%, the peak value of CH does not decrease significantly. Therefore, adding 5% silica fume is the best for the water-promoting effect of carbon nanotube cement-based composite materials. It can be found that the peak value of SiO₂ is very low. This is mainly because most of the SiO₂ has reacted with the hydration products at the 28-day age, which is in agreement with Khaloo's study [26].

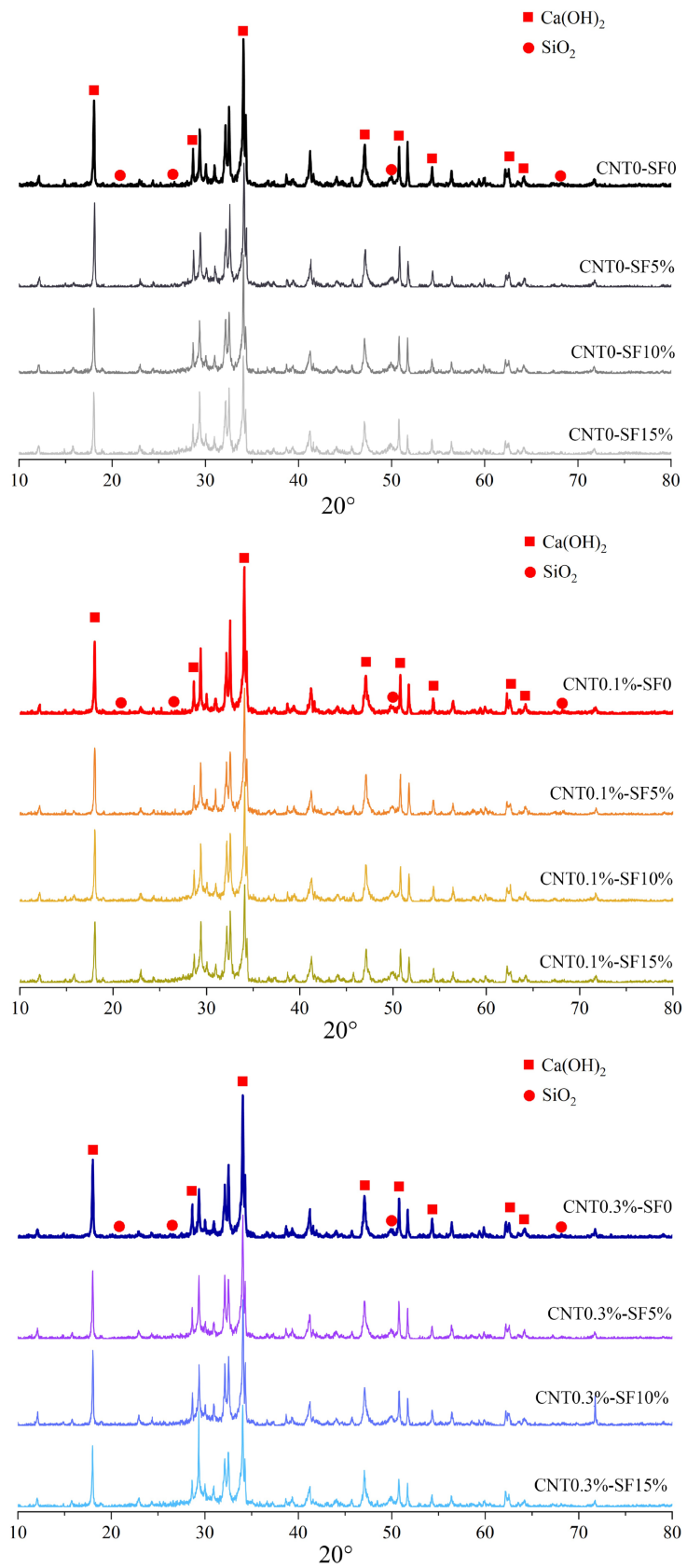


Figure 5. Results of XRD.

3.3. Analysis of Damping Performance

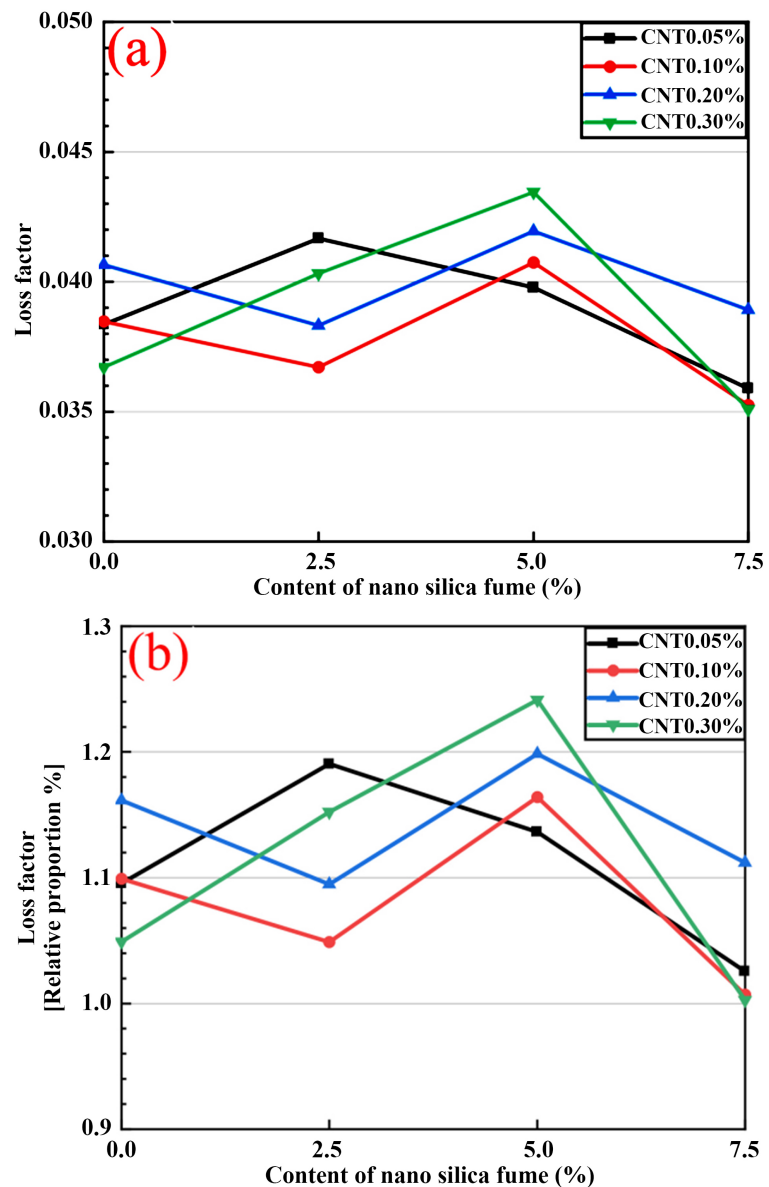


Figure 6. Loss factor of CNT-nano silica fume-modified cement pastes.

Figure 6 shows the loss factor of carbon nanotube-silica fume-cement composite material. It can be seen that adding an appropriate amount of silica fume can further improve the damping performance of the carbon nanotube cement composite material. Among them, when the silica fume content is 5%, and the carbon nanotube content is 0.3%, the composite material has the best loss factor, which is 24% higher than the control group. This is mainly because silica fume promotes the dispersion of carbon nanotubes in the cement matrix, enhances the interface between carbon nanotubes and the cement matrix, and makes more carbon nanotubes participate in vibration friction, thereby dissipating more energy. After the silica fume content is increased to 7.5%, the loss factor of the cement composite

material decreased significantly.

3.4. Pore Structure

Based on the damping performance results, this experiment further studied the pore structure characteristics of the trial specimens with the optimal loss factor ratio, including their porosity, critical pore size, and average pore size, as listed in Table 3. In Figure 7, Figure 8 and Table 3, it can be seen that the critical pore size and average pore size of the cement-based composite material with single carbon nanotube addition do not change much. When nano-silica and carbon nanotubes are co-doped, the pore size distribution curve of the cement-based composite material will continuously shift inward as the nano-silica content increases. The critical pore size and average pore size of the cement-based composite material with nano-silica and carbon nanotubes co-doped are further reduced compared to that of the cement-based composite material with nano-silica single-doped, which indicates that nano-silica and carbon nanotubes have a good synergistic effect in optimizing the pore size structure of the cement-based composite material. For composites incorporating 7.5% nano-silica ash and 0.2% carbon nanotubes, there was a 33.3% reduction in average pore size and an 88.9% reduction in critical pore size, respectively. In terms of porosity, the porosity of cement-based composite materials generally decreased with the addition of nano-silica and carbon nanotubes, but increased slightly in the cement matrix with the addition of 0.2% carbon nanotubes, which may be due to the formation of large pores and voids caused by the agglomeration of some carbon nanotubes.

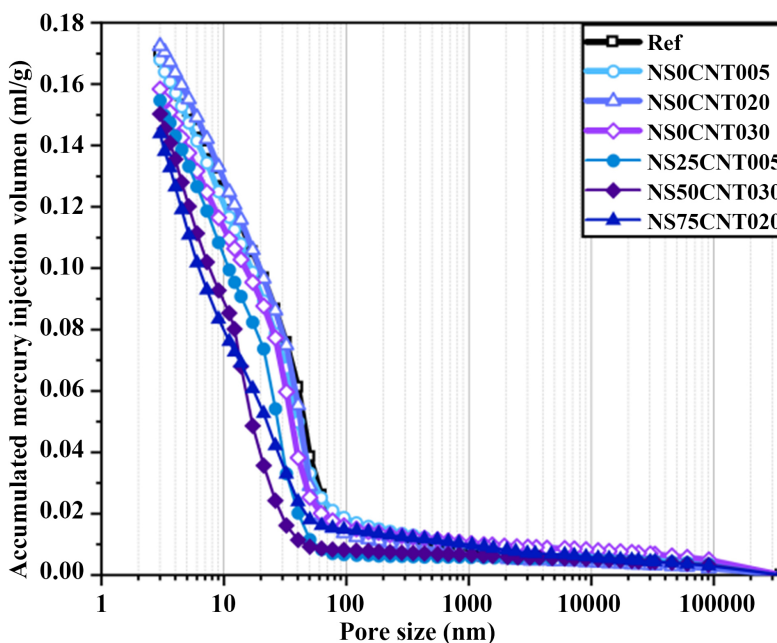


Figure 7. Cumulative pore size distribution of CNT-nano silica fume-modified cement pastes.

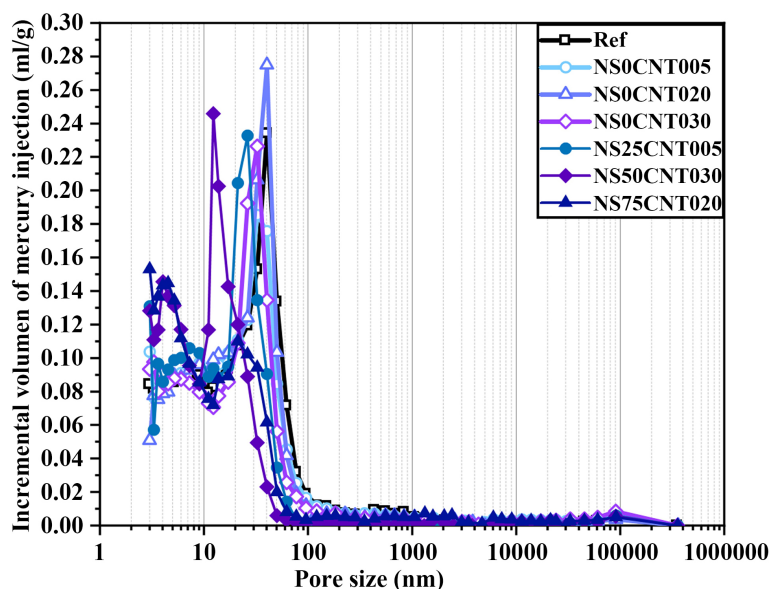


Figure 8. Pore size distribution of CNT-nano silica fume-modified cement pastes.

Table 3. MIP results of the CNT-nano silica fume-modified cement pastes.

Number	Porosity (%)	Average pore size (nm)	Critical pore size (nm)
Ref	27.74	13.5	40.3
NS0 CNT005	27.59	12.8	32.4
NS0 CNT020	27.96	13.8	40.3
NS0 CNT030	26.17	13.4	32.4
NS25 CNT005	25.78	11.1	26.3
NS50 CNT030	25.20	9.0	12.3
NS75 CNT020	24.01	9.0	4.5

3.5. Mechanical Property Analysis

It can be found from **Figure 9** that silica fume can significantly enhance the compressive strength of cement-based composite materials. Among them, when the nanoscale silica fume content is 5%, and the carbon nanotube content is 0.1%, the composite material has the highest compressive strength (84 MPa), which is 25.3% higher than the control group. When the carbon nanotube content is increased to 0.3%, the compressive strength of the composite material shows a significant decrease, which may be due to the fact that the carbon nanotube content is far greater than the optimal content. **Figure 10** shows the flexural strength of carbon nanotube-nanosilica-cement-based composite materials. It can be seen that nanosilica can improve the flexural strength of the composite material. When the nanosilica content is 7.5%, and the carbon nanotube content is 0.1%, the flexural strength of the composite material is 53% higher than the control group. It can also be found that when nanosilica and carbon nanotubes are co-doped, the optimal content of carbon nanotubes is close to 0.2%. After the carbon nanotube

content is increased to 0.3%, the flexural strength also shows a significant decrease. The advancement in mechanical properties is mainly due to the fact that nanosilica can promote hydration, fill the pore structure of cement matrix, and reduce the porosity of the composite material. At the same time, appropriate amount of silica fume can mechanically disperse carbon nanotubes, reduce the size of carbon nanotube agglomeration, and further improve the compressive and flexural strength of single-doped carbon nanotube cement-based composite materials.

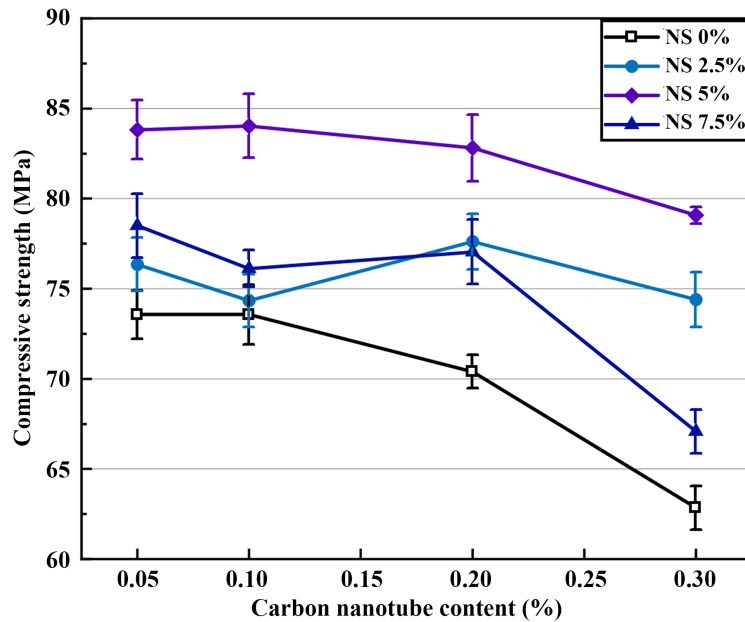


Figure 9. Compressive strength of CNT-nano silica fume-modified cement pastes.

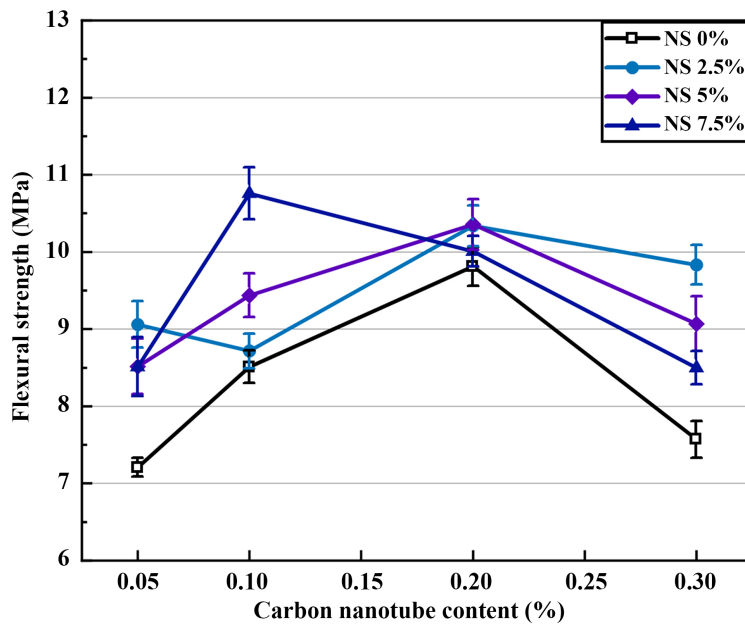


Figure 10. Flexural strength of CNT-nano silica fume-modified cement pastes.

4. Conclusions and Discussion

4.1. Dispersion of Nano-Silica Fume

The introduction of nano-silica significantly improved the distribution of carbon nanotubes within the cement matrix, as clearly verified by the scanning electron microscope images. When a small amount of nano-silica was added to the cement matrix, some agglomerated carbon nanotubes came into full contact with the nano-silica, and mechanical action dispersed the agglomerates into smaller agglomerates or even single dispersed carbon nanotubes. This dispersing phenomenon is attributed to the high surface-to-volume ratio of nano-silica and its ability as a dispersant, thus reducing the Van der Waals force between carbon nanotubes.

4.2. Optimization of the Pore Structure

The addition of nanoscale silica fume not only effectively reduces the critical pore size and the average pore size of the cement-based composite material, but also exhibits good synergistic effects with carbon nanotubes, which can significantly optimize the pore structure. Experimental data indicates that the cement-based composite material with 0.2% carbon nanotubes and 7.5% nanoscale silica fume exhibits a 33.3% reduction in average pore size and an 88.9% reduction in critical pore size in comparison with the control group. The optimization of the pore structure helps to improve the material's density and impermeability. Further research can delve deeper into the effects of pore structure optimization on the material's durability and long-term performance, and assess its potential for practical engineering applications.

4.3. Impact on Mechanical Properties

The addition of nano-silica can further enhance the mechanical properties of cement-based composite materials containing carbon nanotubes alone. With the increase of nano-silica content, the flexural and compressive strength of the material shows a trend of first rising and then falling. The results reveal that the inclusion of nano-silica and carbon nanotubes can improve compressive strength and flexural strength by up to 25.3% and 53%, respectively. This improvement is mainly attributed to the effective dispersion of nano-silica, which makes carbon nanotubes more uniformly dispersed in the cement matrix, promotes the cement hydration reaction, and optimizes the pore structure of the matrix. It can be further explored why the mechanical properties of the cement-based composite materials decline when nano-silica is over-added, in order to avoid the decline of the mechanical properties of the materials.

4.4. Impact on Damping Performance

The addition of nano-silica further improved the loss factor of the carbon nanotube cement-based composite material. When 0.3% carbon nanotubes and 5% nano-silica were added, the material's loss factor was increased by 24%. This phenomenon is mainly due to the effective dispersion of large-sized agglomerates of

carbon nanotubes by nano-silica, allowing more carbon nanotubes to participate in the friction energy dissipation process. Improving the damping performance of the material is of considerable significance for improving its seismic and impact resistance. Future research can further explore the impact of various combinations of nano-silica and carbon nanotube additions on the loss factor and assess its long-term stability and effectiveness in practical applications.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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