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Original Research Article

Comparison of compressive strength and electrical resistivity of cementitious composites with different nano- and micro-fillers

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ABSTRACT

Cementitious composites with 0–1.5 wt.% Nano-SiO_2 (NS), nano-TiO_2 (NT), carbon nanotubes (CNTs), carbon nanofibers (CNFs) and carbon microfibers (CFs) are fabricated and tested. The enhancing effects of different fillers on the compressive strength and electrical resistivity of composites are compared, and the underlying modification mechanisms of fillers to composites are investigated by analyzing the difference in the morphology of fillers and rheology of composites. The compressive strength of composites containing 0.1% NS, 0.5% NT, 0.1% CNTs and 0.5% CFs by weight of cement presents approximately 12.5%, 20.8%, 16.8% and 21.4% higher than that of control sample, respectively. It is revealed that CFs also have improving effect on the compressive strength of composites besides flexural strength. When the composites with nano-fillers cannot be processed to ideal state, the reinforcing effect of nano-fillers is no better but even worse than that of micro-fillers. Composites with CNTs, CNFs and CFs possess good electrical conductivity. Composites with CNFs and CFs have a percolation threshold of electrical resistivity below 0.5%, while the percolation threshold of electrical resistivity of composites with CNTs is about 1%. Although CNFs do not have significant effect on compressive strength of composites, they have the best improvement to electrical resistivity.

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1. Introduction

Cementitious materials (including cement paste, cement mortar and concrete) are widely used in construction industry for their high strength, low cost, simple construction and wide applicability. However, some disadvantages limit the use of cementitious materials such as poor durability and relatively low flexural strength. An effective method to mend these shortages is adding micro/nano fiber or nano particle fillers into cementitious materials [1–4], as the mechanical strength and service life of cementitious composites are determined by the micro-structure and by the mass transfer in nano-scale [5]. The extremely fine size makes nano and micro fillers exhibit unique physical and chemical properties [6]. In addition, the composites with nano- and micro-fillers will exhibit excellent electrical conductivity [7,8] and piezoresistivity [9–11]. They can be applied as anti-corrosion earth connectors for electrical-shock protection and electric-heating pavement materials for de-icing roads [12–14].

In recent years, many studies have been done about the mechanical and electrical properties of cementitious composites mixed with different types of fillers, and some of these studies have obtained considerable enhancements. For example, nano particles (e.g. nano-SiO_2 (NS) [15,16], nano-ZrO_2 [15], nano-TiO_2 (NT) [17–19]) can strengthen the composites by nucleus effect [15,18], filling effect [16] and hydration acceleration effect [15,18,19]. Nano and micro fibers (e.g. carbon nanotubes (CNTs) [20–24], carbon nanofibers (CNFs) [22], and carbon microfibers (CFs) [25]) mainly enhance the composites by forming an enhancing network [20,22,26] and improving bonding strength [22,23,25,27]. Especially the CFs which have good conductivity can also be used for developing electrically conductive cementitious composites [24,28]. In addition to the difference of enhancing effect between particle fillers and fiber fillers, fiber fillers with different aspect ratios and particle fillers with different specific surface areas may affect their enhancing effects. Moreover, although nano-fillers can take effect in lower content, their practicability is limited by high price and difficult fabrication processes [29,30]. The study on comparison of the enhancing effect of different fillers helps to choose the right filler under different conditions. However, little work has been done on comparison of the enhancing effect of different fillers based on their dimensions or size scales. The influences of different types of fillers, e.g. nano- and micro-fibers, particle and fiber fillers on the mechanical and electrical properties of cementitious composites have not been studied. The different enhancing mechanisms among them have not been explained by morphological characteristics of different fillers and rheology of composites.

In this paper, we choose five representative nano- and micro-fillers, which are NS, NT, CNTs, CNFs and CFs. Cementitious composites mixed with different fillers by 0–1.5 wt% are fabricated and tested for compressive strengths and electrical resistivity. The enhancing effect and the corresponding mechanisms are explained by analyzing the difference in the morphology of fillers and rheology of composites.

2. Experimental programs

2.1. Materials

The raw materials used to fabricate cementitious composites include cement, water, water reducer and fillers. The chemical composition of P.O 42.5 R cement is shown in Table 1. The water reducer is 3310E polycarboxylate superplasticizer. Its solid content is 45% and it can reduce water to an extent of 30%. In order to compare the enhancing effect of different fillers on cementitious materials, five types of representational fillers are chosen in this paper. 0D nano particle fillers include NS and NT. 1D nano carbon fiber fillers include CNTs and CNFs. 1D micro carbon fillers are CFs in lengths of 3 mm and 6 mm.

The NS is hydrophilic type and the physical parameters of NT and NS are shown in Table 2. The CNTs are multi-walled and the CNFs are PR-24-XT-HHT type. The Physical properties of CNT and CNF are shown in Table 3. Performance parameters of 3 mm and 6 mm PAN-based CFs are shown in Table 4.

Table 1 – Chemical composition of cement.

Chemical Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O
Wt.%	61.13	21.45	5.24	2.89	2.08	2.05	0.77

Table 2 – Physical properties of NS and NT.

Type	Diameter/nm	Specific surface area/$m^2\ g^{-1}$	Density/$g\ cm^{-3}$	pH	Purity/%
NS	12	200	60	4.5	≥99.8
NT	10	150	–	–	≥99

Table 3 – Physical properties of CNT and CNF.

Type	Diameter/nm	Length/μm	Specific surface area/$m^2\ g^{-1}$	Conductivity/$s\ cm^{-1}$	Purity/wt%
CNT	>50	10–20	>60	>100	>95
CNF	100	50–200	230	–	–

Table 4 – Physical properties of CFs.

Diameter/ μm	Tensile strength/MPa	Tensile modulus/GPa	Density/ g cm^{-3}
7	3450	230	1800

2.2. *Preparation*

The water to cement ratio (i.e. w/c ratio) was fixed at 0.2 and the superplasticizer (0.75% by weight of cement) was added in each sample. NS, NT, CNTs and CNFs were added to the paste at dosages of 0.1%, 0.5% and 1.0% by weight of cement, respectively. 3 mm CFs and 6 mm CFs were added to the paste at dosages of 0.5%, 1.0% and 1.5% by weight of cement. The mix proportions of cement paste with different fillers at different dosages are tabulated in Table 5. A sample named NS01 means that 0.1 wt.% NS was added to the specimen. The other sample names follow the same rule.

The fabrication process of cementitious composites is as following: (1) The raw materials were weighed by a electronic balance following the mix proportions. (2) A cement paste mixer was used to mix the water, filler and superplasticizer for 30 s in low speed to disperse the filler into the solution. Also, a probe sonicator was used to disperse the CNTs and CNFs for 5 min instead of the mixer as it is difficult to disperse them well with mixer. (3) The cement was put into the mixture slowly with a stir at 100r/min with the cement paste mixer, and this mixture was stirred for 3 min at 500 rpm. (4) After the mixture was poured into the molds of 40 mm × 40 mm × 40 mm, it should be vibrated to reduce air bubbles. (5) Two stainless-wire-electrodes were embedded at both position 10 mm far away from the sides and vibrate for another 5 s. (6) The specimens were put into the curing chamber at temperature of 20.0 °C and 95% relative humidity for 24 h. Then, they were unmolded for water environment curing for 28d.

Table 5 – Mix proportions of the cement paste with different fillers (by weight of cement).

Samples	Cement	Water	Fillers/%	Superplasticizer/%
Control	1	0.2	0	0.75
NS01	1	0.2	0.1	0.75
NS05	1	0.2	0.5	0.75
NS10	1	0.2	1	0.75
NT01	1	0.2	0.1	0.75
NT05	1	0.2	0.5	0.75
NT10	1	0.2	1	0.75
CNT01	1	0.2	0.1	0.75
CNT05	1	0.2	0.5	0.75
CNT10	1	0.2	1	0.75
CNF01	1	0.2	0.1	0.75
CNF05	1	0.2	0.5	0.75
CNF10	1	0.2	1	0.75
3CF05	1	0.2	0.5	0.75
3CF10	1	0.2	1.0	0.75
3CF15	1	0.2	1.5	0.75
6CF05	1	0.2	0.5	0.75
6CF10	1	0.2	1.0	0.75
6CF15	1	0.2	1.5	0.75

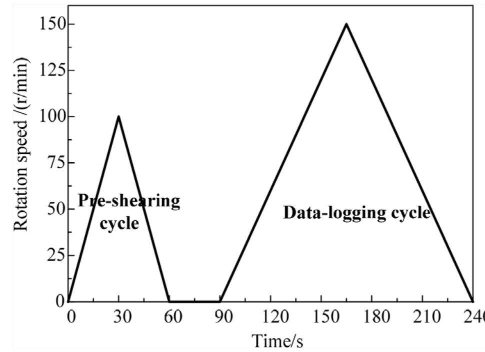

Fig. 1 – Program of rheological properties measurement.

2.3. *Measurement*

2.3.1. *Rheological test*

After stirring, rheological tests were immediately conducted for fresh cement pastes by a Brookfield RST-SST rotational rheometer. The program of rheological properties measurement is shown in Fig. 1. In the first phrase, i.e. "pre-shearing cycle", the rotation rate is accelerated from 0 to 100 rpm in 30 s and reduced to 0 for another 30 s aiming to get the same shear state for each mixture before measurement of rheology. After a stand for 30 s the second phrase, i.e. "data-logging cycle" is performed. In this phrase the rotation rate increases from 0 to 150 rpm in 75 s and then returns to 0 for another 75 s. 150 data points were recorded for once per second to obtain the shear stress-shear rate curves of the cement paste [31].

2.3.2. *Mechanical test*

The compressive strength tests were performed through displacement-controlled loading at a speed of 1.2 mm/min by using an electro-hydraulic servo universal testing equipment.

2.3.3. *Electrical resistance test*

The electrical resistance of specimens was tested by two-electrode method using an LRC meter at the frequency of 100 kHz.

3. Results and discussion

3.1. *Comparison of compressive strength of composites with different fillers*

3.1.1. *Comparison of strength of composites with different nanoparticle fillers*

The absolute and relative increases of the compressive strength of cementitious composites with different fillers are summarized in Table 6. Fig. 2 shows the compressive strength of cementitious composites with NT and NS. As shown in Fig. 2, the strength of the composites with NT is higher than that of the composites with NS at the same filler content. In addition, the compressive strength of the NS composites increases with the increasing NS content up to 0.1%, and then decreases with the NS content.

Table 6 – Absolute increase and relative increase on compressive strength of cementitious materials with different fillers.

Sample type	Dosage/%	Increase value/MPa	Percent of increase/%
With NS	0.1	16.2	12.5
	0.5	14.9	11.5
	1.0	3.4	2.6
With NT	0.1	17.1	13.2
	0.5	27.0	20.8
	1.0	14.2	10.9
With CNT	0.1	21.8	16.8
	0.5	12.9	10.0
	1.0	-4.6	-3.5
With CNF	0.1	-2.3	-1.8
	0.5	-1.4	-1.1
	1.0	-37.2	-28.6
With 3 mm CF	0.5	22.5	17.3
	1.0	22.9	17.6
	1.5	22.1	17.0
With 6 mm CF	0.5	27.7	21.4
	1.0	27.6	21.2
	1.5	19.7	15.2

The compressive strength of the composites with NT versus filler content has the same trend as that of the composites with NS. However, the maximum compressive strength appears when the NT content is 0.5%. It can be seen from Table 6 that the largest absolute and relative increments of the NS composites are 16.2 MPa and 12.5%, respectively. NT can achieve the largest absolute and relative increments of 27.0 MPa and 20.8%, respectively. Therefore, NT has better reinforcing effect to cementitious materials compared with NS.

Based on existing researches, NS can strengthen the composites by providing nucleus, filling the void space and reacting with cement hydration products [15,27]. NS helps hydration products grow and enhances the microstructure. NT cannot react with Portland cement and water, but it can also accelerate the early age hydration and increase hydration degree of Portland cement [18]. The hydration products can fill the pore of cementitious composites. This makes cement matrix much denser. However, because the w/c ratio is extremely low, adding nano powders will significantly thicken

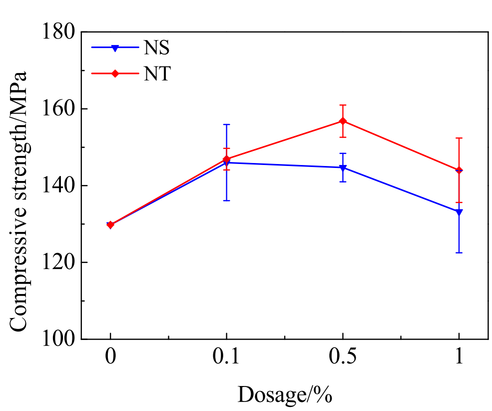

Fig. 2 – Comparison of strength of composites with different nanoparticle fillers.

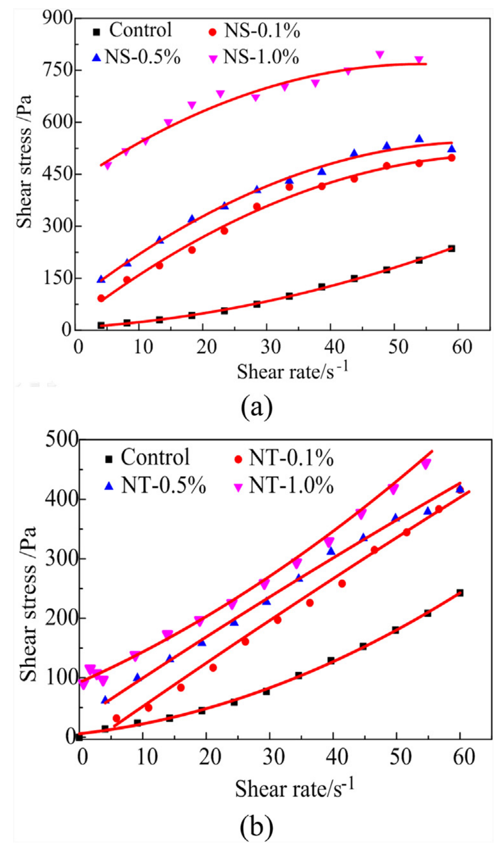

Fig. 3 – Rheological characteristics of cement paste with (a) NS and (b) NT.

the paste. Fig. 3 shows rheological characteristics of cement pastes with NS and NT extracted from rheometer, respectively. It is indicated from the flow curves that the higher the shear stress is, the poorer fluidity the cement paste presents. It can be seen from Fig. 3 that the flowability of cement paste with NS sharply turns worse above the content of 0.5%. Yield stress as one of the rheological parameters is the minimum shear stress that drives material to initiate flow and deformation, which is reflected as the intercept of Y axis. The yield stress of cement paste with NS above 0.5% increases sharply. This indicates that rheology of cement paste is more influenced by NS than NT. It is mainly caused by the different surface characteristics of them. NS is hydrophilic and has larger specific surface area in respect to NT. Thus, much water is adsorbed onto the surface of NS. As a result, less free water leaves in the cement paste of NS. Poor fluidity of cement paste may cause internal defects in specimens, which can confine the development of strength of composites with high content of nano particle fillers. Therefore, the compressive strength of NS decreases after the content is above 0.1%. The volume content of NT is lower than NS with the same mass content, because NT has greater density. Therefore, the strength of composites with NT is less affected and does not decrease early.

3.1.2. *Comparison of strength of composites with nanoparticle filler and nanofiber filler*

Fig. 4 shows compressive strengths of cementitious composites with different nano particle fillers (i.e. NS and NT) and

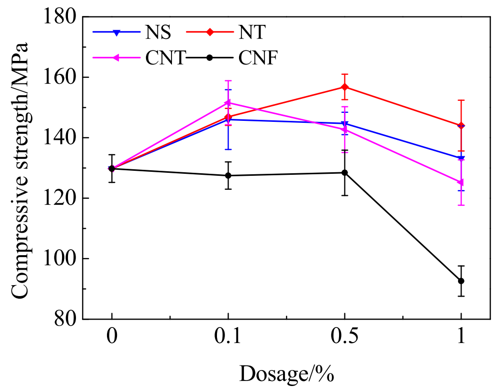

Fig. 4 – Comparison of strength of composites with different nanoparticle fillers and nanofiber fillers.

nano fiber fillers (i.e. CNTs and CNFs). It can be seen from Fig. 4 that the compressive strength of the composites firstly increases and then decreases with the increasing CNT content. When the CNT content is 0.1%, the compressive strength of composite achieves the largest absolute and relative increments of 21.8 MPa and 16.8%, respectively. Fig. 5 shows the rheological characteristics of cement pastes with CNTs and CNFs. It indicates that 0.1% of CNTs have unobvious effect on the yield stress of cement paste, but 0.1% of CNFs obviously raises the yield stress of cement paste. Cement pastes with 0.5% CNTs and CNFs are obviously thick, and those with 1% fillers are over the measurement range of the rheometer. As a result, the strengths of cementitious composites with nano fibers above 0.5% may be restricted due to poor fluidity of the composites. However, CNFs show negative effect on the compressive strength of composites. The compressive strength indicates a trend of continually decrease with the increasing CNF content. In this paper, nano fiber fillers are not as good as nano particle fillers in terms of reinforcing effects on compressive strength. While in the case of low content, CNTs show better enhancing effect on cementitious composites. The enhancement of CNTs on the compressive strength of cementitious composites is due to the following reasons. Interfacial interactions between nanotubes and hydrations (such as C–S–H and calcium hydroxide) of cement may produce a high bonding strength and increase the load-transfer efficiency across the voids and cracks. Moreover, the addition of carbon nanotubes fines pore size distribution and decreases the porosity of cement composites [26,30]. Besides, 0.1% of CNTs has little effect on the yield stress of composites, which means the fluidity of composites does not significantly degrade. An extensive distributing enhancement network of nano-fiber in cementitious composites results in the enhancement on strength. However, it is difficult to disperse the CNFs uniformly in the cement matrix. It is because nanofibers have high specific surface area and extreme small size which make them easy to agglomerate. Poor dispersion of nanofiber fillers in cement paste may cause internal defects and weaken the enhancing effects on mechanical properties. When the nano fibers firm large bundles, sliding among fibers can actually decrease the composite strength. Hence, the composites with CNFs show poor enhancement on compressive strength. CNTs have better reinforcing effect to cementitious composites for their hollow cylindrical structure, but the problem of agglomeration remains. The compressive strength of composites reveals a trend of decrease after 0.5% content of CNTs and CNFs due to the problem of agglomeration and poor fluidity which can be seen in Fig. 5.

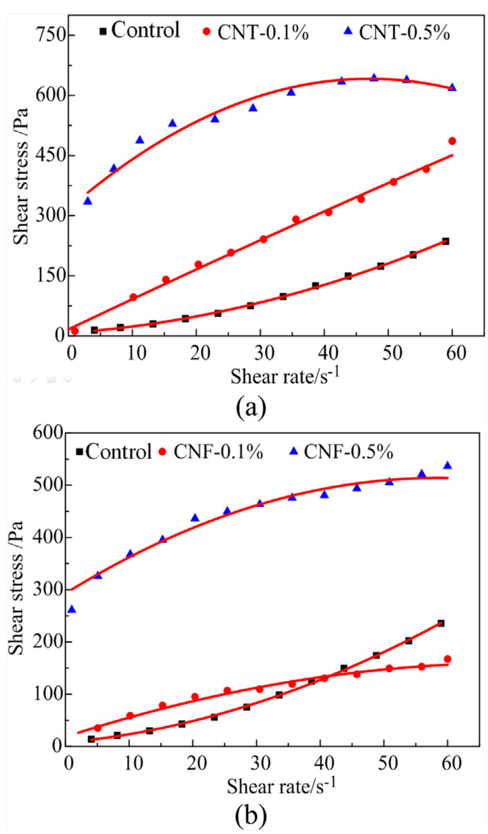

Fig. 5 – Rheological characteristics of cement paste with (a) CNT and (b) CNF.

3.1.3. *Comparison of strength of composites with nanofiber filler and microfiber filler*

Fig. 6 shows compressive strengths of cementitious composites with nano-fiber fillers (i.e. CNTs and CNFs) and micro-fiber fillers (i.e. 3 mm and 6 mm CFs). It can be seen from Fig. 6

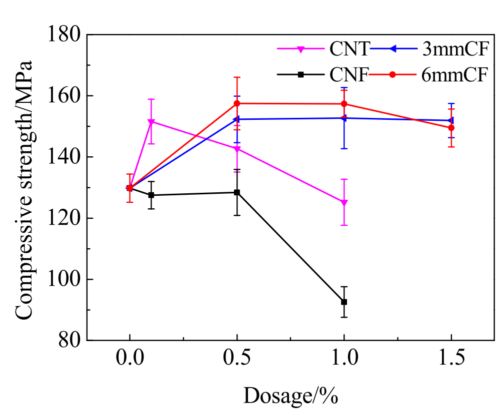

Fig. 6 – Comparison of strength of composites with nanofiber filler and microfiber filler.

that the compressive strengths of cement composites raise to a higher level when CFs are added to composites. Composites with 0.5% and 1.0% CFs with a length of 6 mm have higher compressive strength than that with 3 mm CFs. While the compressive strength of composites with 1.5% 6 mm CFs decreases and is lower than that with 3 mm CFs. It can be seen in Fig. 7 that the fluidity of cement paste with CFs below 1% is good, while that of cement paste with 1.5% CFs is poor, especially the 6 mm CFs, whose yield stress is above 200 Pa. This indicates that 6 mm CFs are more likely to twine around than 3 mm CFs at high filler content. This can explain why in content of 1.5% composites with 6 mm CFs is inferior to that with 3 mm CFs. The compressive strength of composites with CFs increases a little after the content of CFs increases above 0.5%. As listed in Table 6, the largest absolute and relative values of enhancement are 27.7 MPa and 21.4% as filler content is 1.0%. This means that the optimal amount of CFs is between 0.5% and 1.0%, while that of CNTs is 0.1%. In general, microfiber fillers have better reinforcing effect to cementitious materials, while nanofiber fillers can provide good enhancing effect at a low content. For long time, researchers have generally accepted that nano materials possess extraordinarily good enhancing effect to cementitious composites as they have small size effect and surface effect, especially with very low content. However, the research of this paper indicates that when the cement paste with nano fillers cannot be processed to ideal state, the improving effect of nano fillers is no better but even worse than micro fillers. In this case, using micro fillers to improve the mechanical properties of cementitious composites is a reasonable choice. Moreover, the enhancing mechanism of fibers on mechanical properties of cementitious composites is known as restricting the development of cracking, mitigating stress concentration and increasing the energy absorption capacity. It is generally accepted that carbon fibers significantly affect flexural strength rather than compressive strength of cementitious composites. This paper shows that CFs obviously enhance the compressive strength of cementitious composites as well. The reason is that carbon fibers restrict the development of longitudinal cracks as the specimen is under pressure, hence the compressive strength is improved.

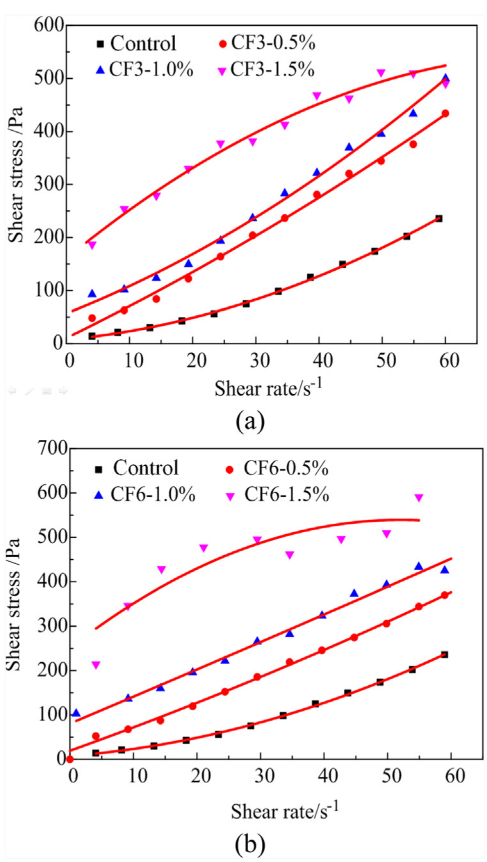

Fig. 7 – Rheological characteristics of cement paste with (a) 3 mm CF and (b) 6 mm CF.

3.2. *Comparison of electrical resistivity of composites with different fillers*

3.2.1. *Comparison of resistivity of composites with different nanoparticle fillers*

Table 7 gives the absolute decrease and relative decrease of electrical resistivity of cementitious composites with different fillers against plain cementitious composites. Fig. 8 shows electrical resistivity of cementitious composites with NT and NS. As shown in Fig. 8, the electrical resistivity of cementitious composites with NS first slightly decreases and then increases. The resistivity of the composites with NT has a continual decline and is lower than that of the composites with NS at the same filler content. It can be seen from Table 7 that NT can achieve the largest decrease of resistivity by 42.6% to a resistivity of 4.15 kΩ cm. This is because NT is semiconductive, which has low resistivity itself. In addition, it is unstable and can excite more free electrons to get higher conductivity. Therefore, cement paste mixed with NT, which possesses characteristics of semiconductor, has electrically conductive

Table 7 – Absolute and relative decrease on electrical resistivity of cementitious materials with different fillers.

Sample	Dosage/%	Decrease volume/kΩ cm	Percent of decrease/%
NS	0.1	1.12	15.5
	0.5	1.03	14.2
	1.0	−1.36	−18.7
NT	0.1	2.37	32.8
	0.5	2.00	27.6
	1.0	3.08	42.6
CNT	0.1	0.40	5.6
	0.5	3.99	55.2
	1.0	6.66	92
CNF	0.1	3.25	45
	0.5	6.99	96.6
	1.0	7.17	99.1
3mmCF	0.5	5.89	81.5
	1.0	6.44	89
	1.5	6.68	92.4
6mmCF	0.5	6.53	90.3
	1.0	6.59	90.2
	1.5	6.63	90.7

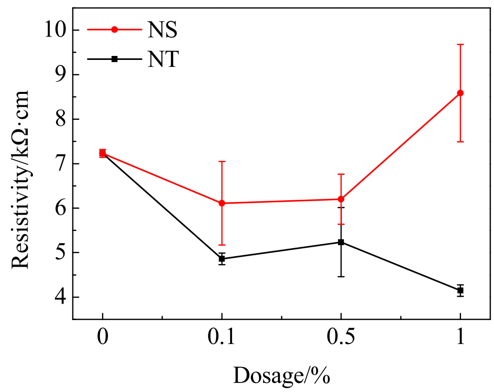

Fig. 8 – Comparison of resistivity of composites with different nanoparticle fillers.

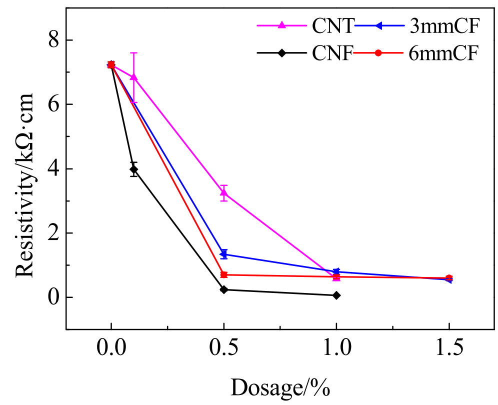

Fig. 10 – Comparison of resistivity of composites with nanofiber filler and microfiber filler.

property [29]. On the other hand, NS as a kind of insulating material, cannot cause decrease of resistivity. In general, the electrical resistivity of composites added with non conductive filler is related to the internal voids and microstructure of mixtures [15,32]. The denser the matrix is, the higher electrical resistivity becomes. However, in this paper the content of nano filler incorporated into cement is relatively low, which cannot match the above principle.

3.2.2. *Comparison of resistivity of composites with nanoparticle filler and nanofiber filler*

Fig. 9 shows electrical resistivity of cementitious composites with nano particle and nano fiber fillers of different dosages. As shown in Fig. 9, the resistivity of composites with CNTs and CNFs continuously decreased with the increase of dosage. The resistivity of composites with CNTs is always higher than that of composites with CNFs at the same filler content. The resistivity of composites with CNFs drops sharply in the dosage range from 0.1% to 1%, which illustrates that the percolation threshold zone is between the content from 0.1% to 1%. The threshold zone of composites with CNFs is in the range from 0 to 0.5% content. When the content of CNFs reach 0.5%, the electrical resistivity of the composites is 0.24kΩ cm, which decreases to 1/30 of the composites without CNFs.

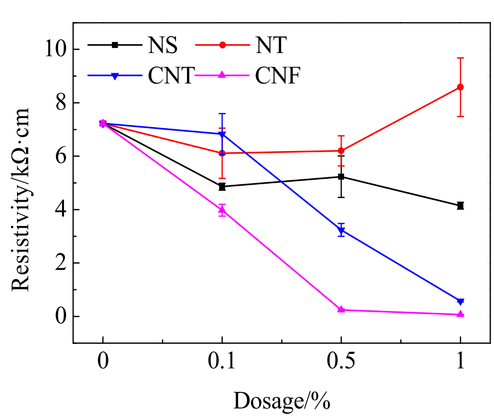

Fig. 9 – Comparison of resistivity of composites with nanoparticle filler and nanofiber filler.

Above percolation threshold, continuous conductive paths are attained and the resistivity changes little. As shown in Table 7, the lowest resistivity appears at 1% CNTs and CNFs, decreasing by 92% and 99.1%, respectively. Although CNFs do not have much effect to compressive strength, it can effectively reduce the electrical resistivity of cementitious materials. Compared with NS and NT, CNTs and CNFs have a completely different conductive mechanism which contributes to superior conductivity. Some researches indicate that the extremely high aspect ratios of carbon nano-fibers make them easy to form a conductive network with a doping level as low as 0.1 wt.% [33–36], which illustrates that cementitious composites with carbon nano-fibers have distinct advantage compared with other nano-fillers.

3.2.3. *Comparison of resistivity of composites with nanofiber filler and microfiber filler*

The electrical resistivity of cementitious composites with nanofiber fillers and microfiber fillers of different dosages is illustrated in Fig. 10. As shown in Fig. 10, the electrical resistivity of composites with 3 mm and 6 mm CFs decreases rapidly with the increasing content of fillers from 0 to 0.5%, and that of composites with 6 mm CFs is lower than that of the composites with 3 mm CFs at the same filler dosage. This is due to long fibers are more probable to connect with each other. The resistivity of composites with 3 mm and 6 mm CFs decreases by 81.5% and 90.3% at the filler content of 0.5%, respectively. Above this dosage, the resistivity decreases slowly. This indicates that the percolation threshold of cementitious composites with 3 mm and 6 mm CFs are between 0 and 0.5%. It can be seen from Table 7 that the largest relative decrease of resistivity are 92.4% and 90.7%, respectively. The resistivity of composites with microfiber fillers is higher than that of the composites with CNFs but lower than that of the composites with CNTs at the same filler content. Nanofiber fillers are small in size which can form conductive networks at a low dosage, so they have better enhancement effect to electrical conductivity of composites. However, CNTs as nanofiber filler is too short to form networks at a low content. Although composites with CNFs show better conductivity in this study, composites with CFs may possess superior capability of electrical conductivity in long-distance network because of the longer fiber length.

4. Conclusion

In this paper, the enhancing effects of different nano- and micro-fillers to cementitious materials on compressive strength and electrical resistivity were compared and analyzed. Five representational fillers were chosen in this paper including nanoparticle fillers (i.e. NT and NS), nanofiber fillers (i.e. CNTs and CNFs) and microfiber fillers (i.e. CFs in length of 3 mm and 6 mm). The composites with different contents of fillers were studied to explore the best reinforcing effect and explain their reinforcing mechanisms. The following conclusions can be drawn from the study:

(1) NT, NS, CNTs and 3 mm and 6 mm CFs show enhancing effect on compressive strength by 12.5%, 20.8%, 16.8% 17.6% and 21.4% to cementitious composites at their optimal content, respectively. Cement pastes with high content of nano-fillers are confined by poor fluidity due to the high specific surface areas, which may cause internal defects in specimens. Moreover, it is difficult to disperse the nano fiber uniformly. Therefore, when the cement paste with nano fillers cannot be processed to ideal state, the improving effect of nano fillers is no better but even worse than micro fillers.
(2) CFs have improving effect on the compressive strength to cementitious composites besides flexural strength. The reason is that carbon fibers restrict the development of longitudinal cracks as the specimen is under pressure, hence the compressive strength is improved.
(3) Microfiber fillers have better reinforcing effect to cementitious materials, while nanofiber fillers can provide good enhancing effect at a low content.
(4) CNTs, CNFs and CFs can significantly reduce the electrical resistivity of cementitious composites by 92%, 99.1% and 92.4%, respectively, especially the CNFs, which can decrease the resistivity to a minimum of 0.0625 kΩ cm. Composites with CNFs and CFs have percolation threshold of electrical resistivity below 0.5%, while percolation threshold of electrical resistivity of composites with CNTs is about 1%.
(5) The decrease of electrical resistivity of composites with CNTs is not as large as that of composites with CFs and CNFs because CNTs is too short to form conductive networks at low content. Although CNFs do not have much effect on compressive strength of cementitious materials, it presents the largest decrease in electrical resistivity. Moreover, composites with CFs may possess superior capability of electrical conductivity in long-distance network because of the longer length of CFs.

Ethical Statement

Authors state that the research was conducted according to ethical standards.

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