Research Article

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Investigating the influence of multi-walled carbon nanotubes on the mechanical and damping properties of ultra-high performance concrete

<https://doi.org/10.1515/secm-2020-0046>

Received Sep 03, 2020; accepted Nov 07, 2020

Abstract: In this paper, the effects of multiwalled carbon nanotubes (MWCNTs) on the mechanical and damping properties of ultra-high performance concrete (UHPC) were investigated. The results show that the proper amount of MWCNTs can improve mechanical properties as well as the damping properties. For the mechanical properties, the compressive strength and flexural strength of the specimens increased with the increase of MWCNTs content in the range of 0~0.05% (mass ratio to cement). However, when the content of MWCNTs was more than 0.05wt.%, the mechanical properties of UHPC could not be improved continually because too many MWCNTs were difficult to disperse and agglomerated easily in UHPC. Similar laws also have been found for the damping property of UHPC. The loss factor of UHPC increased with the increase of MWCNTs content in the range of 0 ~ 0.05%. The incorporation of MWCNTs would introduce a large number of interfaces into UHPC, the friction and slip between interfaces were the main reasons for the improvement of the damping property of UHPC. However, when the content of MWCNTs was more than 0.05%, it was difficult to disperse effectively. As a result, the overall energy consumption efficiency of MWCNTs was decreased.

Keywords: UHPC; Carbon nanotubes; Damping property

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1 Introduction

Dynamic loading caused by living loads, sound, wind, and earthquakes conditions are commonly encountered in civil infrastructure systems. The dynamic loading may result in the vibration of structural. Improving the damping of building materials is a way to control the vibration of building structures. The traditional ordinary concrete has a low damping value since it is a brittleness material. It is often considered as a constant value in the design of building structures. Therefore, the damping property of concrete has not been paid enough attention so far.

The existed research on the damping property of concrete is focused on how to improve its damping value, mainly by adding organic polymer [1, 2], latex [3], graphite powder, rubber powder [2], flexible fiber [4, 5] and other materials with high damping. Ahmad Reza Ghasemi *et al.* [6] studied the agglomeration effect of continuously graded single-walled carbon nanotubes (SWCNTs) on the vibration of SWCNTs/fiber/polymer/metal laminates cylindrical shell. Yaser Kiani *et al.* [7] analysed the natural frequencies of composite conical panels made of a polymeric matrix reinforced with uniform or functionally graded carbon nanotubes (FG-CNTs) and found that boundary conditions and angles of embrace of the conical shell play an important role on the fundamental frequencies of the structure. Vibration characteristics of three different types of Single-Walled Carbon Nanotubes (SWCNTs) such as arm-chair, chiral, and zigzag carbon nanotubes have been investigated considering the effects of surface energy and surface residual stresses [8]. Chin K. Leung *et al.* [9] used treated micron and nanometer rubber particles into the concrete. They found that the damping performance of the concrete increased to 600%, but the strength of the concrete was decreased significantly. Amik Collin Hal [10] incorporated coarse aggregates coated with a polymer to improve the damping property of concrete.

The development of nanoscience and nanotechnology provides a new way to improve the performance of

traditional building materials. Multiwalled carbon nanotubes (MWCNTs) have excellent mechanical properties. The tensile strength up to 50 ~ 200GPa, which is 100 times higher than steel. But the density is just only 1/6 of steel. The elastoplasticity of MWCNTs is also very strong, the theoretical elongation is up to 20% and the elastic strain is over 5%. Compared with single-walled carbon nanotubes (SWCNTs), MWCNTs have multi-layered tubular structures, which squeeze and slip each other during deformation. Because of energy dissipation due to friction, MWCNTs exhibit remarkable viscoelastic damping properties [11], it is suitable for damping improvement for cementitious composites. Luo Jianlin *et al.* [12] had studied the basic mechanical properties and damping properties of ordinary cement mortar by adding MWCNTs. It is found that the flexural strength and damping properties of ordinary cement mortar were significantly improved by adding MWCNTs. Therefore, the MWCNTs provide the possibility for improving both of the mechanical and damping properties of UHPC.

Based on the above papers, it can be seen that many scholars have studied how to improve the damping performance of concrete. However, the current research mainly focuses on ordinary concrete. It often leads to a decrease in compressive strength and elastic modulus while improving the damping performance of concrete. Besides, the research on damping performance of ultra-high performance concrete (UHPC) was rare. The MWCNTs have small scale, large specific surface area and excellent mechanical strength. Some scholars have added MWCNTs into epoxy resin. They found that the damping of the epoxy resin was increased by 300%, and the strength of the epoxy resin was also increased significantly. The multi-walled carbon nanotubes (MWCNTs) were introduced into UHPC for increasing mechanical properties as well as damping ratio.

In this paper, the UHPC containing four different content of MWCNTs (0, 0.03 wt.%, 0.05 wt.%, 0.07 wt.%) were prepared. The effects of MWCNTs on the mechanical and damping properties of UHPC were systematically investigated. Firstly, the compressive strength and flexural strength of the specimens were tested. Then, the loss factor of the specimens at different frequencies was measured by Dynamic Mechanical Analysis (DMA). Finally, scanning electron microscopy (SEM) was used to observe the microstructure of the interface transition zone (ITZ) between MWCNTs and the UHPC matrix. The mechanism of the MWCNTs on the mechanical and damping properties of UHPC was discussed.

2 Experimental methods

2.1 Raw materials

The ordinary PI 52.5 Portland cement with 28d compressive strength of 58.6MPa was used, which was produced by Jiangxi Yinshan Cement Co., Ltd. The chemical composition is shown in Table 1. The fly ash was grade I fly ash with a density of 2780 kg/m³. The slag was produced by Nanjing Jiangnan Cement Co., Ltd., with a density of 2910kg/m³. The silica fume was produced by Elkem Shanghai company, China with SiO₂ content of more than 92%. The physical properties and chemical composition of those three materials are shown in Table 2. For the fluidity of concrete, the polycarboxylic acid superplasticizer with a water-reducing ratio of up to 30% was used.

Multi-walled carbon nanotubes (MWCNTs) water dispersion with a mass fraction of 10% were used, manufactured by Nanjing XFNANO Materials Tech Co., Ltd.

Table 1: Chemical composition of cement

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	K ₂ O	TiO ₂	MgO	Na ₂ O	SO ₃	P ₂ O ₅	Cl	NiO
Content (mass%)	53.97	31.15	4.16	4.01	2.04	1.13	1.01	0.889	0.73	0.67	0.13	0.11

Table 2: Chemical composition and physical properties of cementitious materials

Chemical composition (%)	SiO ₂	Fe ₂ O ₃	MgO	Al ₂ O ₃	CaO	SO ₃	LOI	Specific surface area (m ² /kg)	Specific gravity (k/cm ³)
SF	94.5	0.8	0.3	0.3	0.5	0.8	1.0	2200	1.84
FA	55.0	5.9	31.3	31.3	3.9	1.5	1.0	686	2.61
SL	34.2	0.4	14.2	14.2	41.7	1.0	1.7	766	2.63

Table 3: Physical properties of MWCNTs

Outer diameter /nm	Length / μm	Aspect ratio	Purity	Specific surface area
50	10-50	200-1000	>95%	40-300 m^2/g

Figure 1: MWCNTs morphology

The physical properties and morphology of MWCNTs are shown in Table 3 and Figure 1, respectively.

2.2 Mixture design

The UHPC with water to binder ratio of 0.16 was designed [13, 14], the mixture proportion is shown in Table 4. C0 was the mixture without MWCNTs, which was designed as the control group. Three different content of MWCNTs include 0.03wt.% (by weight of cement), 0.05wt.% and 0.07wt.% were added into UHPC, which were shorted for C3, C5, and C7 respectively.

2.3 Specimen preparation

The specimen size of compressive strength and flexural strength test was $160 \times 40 \times 40$ mm. The size of the damping test was designed to be $50 \times 10 \times 5$ mm. The damping test mold and test specimen are shown in Figure 2.

Figure 2: Damping test mold and specimens

The preparation of the specimens was carried out according to the following steps: (1) The cementitious materials, the aqueous dispersion of the MWCNTs, and the water reducer were weighed according to the mixture proportion in Table 4. (2) The water reducer was added into the aqueous dispersion of the MWCNTs and fully mixed and stirred, and the mixture was ultrasonically dispersed at 30°C for 10 minutes. (3) The cementitious material was put into the mixing pot and stirred slowly for 100-120s, then the ultrasonically dispersed mixture was slowly poured into the mixing pot and stirred quickly for 10 minutes to obtain

Table 4: Mixture proportion of MWCNTs reinforced UHPC

Mix No.	CNT content	Cement /g	Slag powder /g	Fly ash /g	Silica fume /g	Water /g	CNT /g	Water reducer /g
C0	0	1036	204	212	69	232	0	22.8
C3	0.03%	1036	204	212	69	228	0.46	22.8
C5	0.05%	1036	204	212	69	225	0.76	22.8
C7	0.07%	1036	204	212	69	222	1.06	22.8

the fresh cement-based composites. (4) The fresh cement-based composites were poured into molds. (5) Then, the mold was placed on the electric vibration table for compaction for the 60s. (6) After 24 hours, the specimens were demoulded and placed in a curing box with a temperature of 20°C and relative humidity of 95% until for 28 days.

2.4 Test setup

2.4.1 Mechanical test

The compressive and flexural tests were carried according to the Chinese Standard GB/T 50081-2002. Three different specimens were tested with each mixture, and the mean value was used as the ultimate compressive and flexural strength.

2.4.2 Damping test

The loss factor (or damping factor) is an important parameter to characterize the damping properties of materials. In this study, the loss factor of MWCNTs reinforced UHPC (50 × 10 × 5 mm) was measured on the Dynamic Mechanical Analysis(DMA). The DMA schematic diagram is shown in Figure 3. DMA test is a technique to measure the dynamic modulus or loss factor of the sample varying with the temperature and frequency. These data were obtained by applying sinusoidal alternating stress to the specimen at a programmed temperature and measuring the change of its strain at the same time. The storage modulus (E'), the loss modulus (E''), and the loss factor ($\tan \delta$) of the material can be obtained simultaneously by DMA test, and calculated according to the Eqs (1)-(5).

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

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

$$E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \quad (3)$$

$$E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta \quad (4)$$

$$\tan \delta = \frac{E''}{E'} \quad (5)$$

Where ω is the angular frequency, δ is the phase angle, t is the time, ε_0 is the strain peak, σ_0 is the stress peak; E'

(a)

(b)

Figure 3: (a) DMA instrument diagram; (b) DMA Schematics

is the energy storage modulus, which refers to the energy stored in the material due to elastic deformation during deformation, reflects the elastic components in the viscoelasticity of the material and characterizes the stiffness of the material; E'' is the loss modulus, which is the energy dissipated in the form of heat due to the viscous deformation of the material during deformation, reflecting the viscous component of the material and characterizing the damping of the material; $\tan \delta$ is the loss factor, which is the ratio of the energy lost during deformation to the maximum storage modulus, that is, E''/E' .

The deformation modes of DMA include single/double cantilever beam mode, compression mode, shear mode, and three-point bending mode. The specimens were subjected to periodic deformation of 0.007 mm with frequencies varying from 0.5 Hz, 1.0 Hz, 1.667 Hz, 2.0 Hz, and 2.5 Hz. All tests were performed at room temperature.

2.4.3 Microstructure

To observe the surface characteristics of MWCNTs reinforced UHPC, JSM-7600F thermal field emission scanning

electron microscope (TFE-SEM) was produced by Japan Electronics Co., Ltd. was used.

The preparation of the test specimens was carried out according to the following steps: (1) The concrete test specimens with diameter no more than 3mm were taken out from the test specimens after the compression test. (2) The test specimens were placed in an oven for baking with a temperature of 60°C for 48 hours. (3) Before the TFE-SEM test, the surface of the test specimens should be sprayed with gold to improve the electrical conductivity of the concrete. (4) The dispersion of MWCNTs in UHPC was observed by TFE-SEM.

3 Results and discussion

3.1 Mechanical Properties

3.1.1 Compressive strength

The compressive strength of MWCNTs reinforced UHPC after 28 days of curing is shown in Figure 4. It can be seen from Figure 4 that the compressive strength of C3, C5, and C7 was 1.4%, 2.7%, and 2.1% higher than that of C0, respectively, which indicated that the content of MWCNTs had a slight enhancement on the compressive strength of UHPC. The reasons for this phenomenon can be summarized as follows. The MWCNTs has excellent mechanical strength and is very small in size, only 10-50 μm in length and its strength is very high, and the ultra-high performance concrete is extremely dense inside, MWCNTs can play a good filling effect after effective dispersion, further reducing the porosity of the UHPC, so that the compressive strength can be slightly improved. However, there were two main reasons why the strength of UHPC doped with MWCNTs had not been greatly increased. First, the failure of concrete was mainly caused by internal tension [15], resulting in cracks. When UHPC was compressed, it will expand and crack laterally, most of the internal failure surfaces were in a compression state, and the proportion of MWCNTs in the crack was small. Therefore, the MWCNTs mixed in do not fully play the bridging role in the crack [16]. The simplified mechanism of MWCNTs bridging is shown in Figure 5. Secondly, the size of MWCNTs is very small, only 10-50 μm , and the width of the crack was 0.1 mm as soon as it was produced. When the cracks were produced, it was difficult for CNT with a too-small size to crossed the cracks and restrained the development of the cracks. However, compared with the concrete with steel fibers [17, 18], the size of steel fibers is much larger than that of MWCNTs, and

the length of steel fiber could reach 13mm. When cracks occurred, the steel fibers could penetrate the cracks completely, so in the process of cracks development, the restraining effect of MWCNTs on cracks was much lower than that of steel fibers, so it was difficult to play the bridging role, so the increment of compressive strength of MWCNTs was limited.

Figure 4: Compressive Strength of MWCNTs Reinforced UHPC

Figure 5: Bridging Mechanism of MWCNTs

Wu [19] found that the compressive strength of UHPC was increased from 98.3MPa to 134.3MPa, 37% higher by added 2vol% steel fibers. He believed that there were micro-cracks, pores, and other weakening areas in the ultra-high performance concrete. The propagation of micro-cracks could begin in the weak region, which will lead to stress concentration at the crack tip under external force. Under tensile loading, the cohesive force distribution could be generated in the crack region around the steel fibers reinforced material. The cohesive force at the crack tip will produce a reactive force field, which could

reduce the stress concentration, restrain the crack growth, and improve the strength. Short fibers reinforced material (6mm) could inhibit the formation of micro-cracks when mixed with hybrid steel fibers reinforced material. When the micro-cracks propagate into micro-cracks under further loading, the short fibers reinforced material around the cracks were gradually pulled out, and the load was mainly borne by the long fibers reinforced material (13mm), which makes the failure of concrete consumed more time and energy [20]. Therefore, the increase of the compressive strength of UHPC with CNT is small.

3.1.2 Flexural property

As can be seen from the figure, the flexural strength of MWCNTs reinforced UHPC with different content of MWCNTs increased at first and then decreased with the increase of MWCNTs content, and reached the highest when the content of MWCNTs was 0.05wt.%. The flexural strength of C3, C5, and C7 was 51%, 68%, and 43% higher than that of C0, respectively, which indicated that the addition of CNT had a notable enhancement on the flexural strength of UHPC. The reasons for this phenomenon can be summarized as follows. First, after ultrasonic dispersion, a large number of MWCNTs were effectively dispersed [21], which made MWCNTs well distributed in the hydrated products of C-S-H phase and enhanced the bridging effect of MWCNTs [22]. Secondly, when the cement specimen was subjected to bending, the micro-cracks were firstly generated in the weak area of the specimen, and the micro-cracks began to expand with the increasing of the force acting on the specimen. At this time, the MWCNTs located at the

micro-cracks will play a bridging role due to its close bonding with the matrix, thus restrained the development and expansion of the micro-cracks [23]. And because of the bending of UHPC, there were a large number of MWCNTs along the whole section of the direction of force, which will play a bridging role, the effective ratio is much higher than that of UHPC under compression [24]. Thirdly, because of the ultra-high performance concrete matrix was extremely dense, and the water-binder ratio is low, so the hydration process after the end of the internal porosity was very small. For ordinary concrete, because of the large difference in aggregate diameter and high water-binder ratio, the formed matrix contained 25-30 vol% pores with diameters of several nanometers to several millimeters, which was much larger than the size of MWCNTs. Some MWCNTs will fell into pores and hardly played a bridging role. The effective ratio of MWCNTs was lower than that of UHPC.

Figure 6: Flexural strength of MWCNTs reinforced UHPC after 28 days of curing

(a)

(b)

Figure 7: (a) Dispersion of MWCNTs in UHPC; (b) Dispersion of MWCNTs in ordinary concrete

The dispersion of MWCNTs in UHPC and ordinary concrete is shown in Figure 7. Fourthly, because of the low water-binder ratio of UHPC, the more contact surface between MWCNTs and matrix, and the better bonding strength between UHPC and MWCNTs, the addition of silica fume in cementitious material will lead to the enhancement of the interface between matrix [25] and MWCNTs and inhibited the generation of cracks.

When the content of MWCNTs was more than 0.05wt.%, the flexural strength was decreased with the increase of the content of MWCNTs. This was because there was a strong van der Waals force between MWCNTs, too much MWCNTs incorporation will lead to mutual adsorption and agglomeration. And the water-binder ratio of UHPC is very low, a large number of MWCNTs could not be effectively dispersed in a small amount of water, and the agglomerated MWCNTs were loosely wound together, which will form defect sites inside the UHPC, and it was difficult to form a strong connection with the matrix, which will have a negative impact when the matrix cracks, so excessive MWCNTs will lead to the reduction of flexural strength.

3.2 Damping property

The loss factors of MWCNTs reinforced UHPC with different mixtures are shown in Figure 8. As can be seen from the figure, MWCNTs-reinforced UHPC shows a minimum loss factor when the MWCNTs content was 0. The loss factor increased with the increase of MWCNTs content in the range of 0 ~ 0.05%. At 2Hz frequency, the loss factors of 0.03% and 0.05% MWCNTs were 89.1% and 98.3% higher than those of the specimens without MWCNTs, respectively. However, when the content of MWCNTs was more than 0.05 wt.%, the loss factor of UHPC could not be increased continually because of the difficulty of dispersing MWCNTs and the agglomeration in UHPC. The loss factor of the specimens with 0.07% MWCNTs is only 15.5% higher than that of the specimens without MWCNTs. The reasons for this phenomenon can be summarized as follows. First, in composites, the damping properties of materials mainly come from the damping properties of materials themselves and the sliding friction energy dissipation system between different materials. The specific surface area of MWCNTs is very large, and a large number of interfaces will be formed in the cement matrix, so the external friction between the MWCNTs interface area and the cement matrix was the main reason to achieve the damping performance of the cement matrix [26–28]. When the cement matrix was strained by an external force, friction

and slippage occurred between MWCNTs and cement matrix, and energy dissipation was realized by converting mechanical energy into thermal energy, to improve the damping performance of the material. Secondly, by adding MWCNTs into the cement matrix, the interface morphology was diverse. When the force was greater than the critical value, friction and slip will occur between the inner and outer walls of MWCNTs, which will further increase the energy dissipation capacity and thus improve the damping capacity [29]. Therefore, with the increase of MWCNTs content, the damping capacity of UHPC will be enhanced. Thirdly, when the amount of MWCNTs is too much, it will lead to mutual adsorption and agglomeration. And the water-binder ratio of UHPC was very low, a large number of MWCNTs could not be effectively dispersed in a small amount of water, the agglomerated MWCNTs were loosely wound together without bonding with the cement matrix, the agglomerated part of the winding could not frictionally slip with UHPC [30–32], the overall energy dissipation efficiency of MWCNTs decreased. Therefore, when the content of CNT was more than 0.05%, the damping capacity of UHPC will be weakened.

Figure 8: Loss factors for MWCNTs-reinforced UHPC with different mixtures

As can also be seen from Figure 8, the loss factors of C0 and C7 varied slightly with increasing frequency, and the loss factors of C3 and C5 increased with increasing frequency. It has been shown that the critical dynamic strain amplitude at the beginning of slip increased with the decrease of frequency. At higher frequencies, slip occurred earlier and the debonding rate was larger [33]. In this experiment, a certain frequency and amplitude of dynamic oscillation force were applied to the specimens, and the

specimens were subjected to periodic deformation of 0.007 mm, resulting in a certain frequency and amplitude of dynamic vibration strain. For a given strain, the slip length was larger for higher frequencies, so the higher the applied frequency, the higher the friction efficiency between MWCNTs and UHPC matrix, the longer the slip length, the more energy dissipation, so the loss factor would increase with the increase of frequency. When the frequency was 2.0 Hz, it was the best frequency for friction slip between MWCNTs and UHPC, and the energy dissipation efficiency would reach the highest, so the loss factor would increase rapidly. However, when the frequency continued to rise, the frequency too fast would lead to the relaxation of the UHPC matrix, weaken the bonding with MWCNTs, and the critical shear stress would decrease, so the increase of loss factor will slow down or even tended to remain unchanged.

To explain the slip energy dissipation effect of MWCNTs, this paper implemented the slip-damping model of MWCNTs by Glaz *et al.* [34] to calculate the theoretical loss factor of MWCNTs, which only accounts for the energy dissipation of aligned matrix inclusions from slippage. The volume content of MWCNTs is 4.37×10^{-4} when the mass ratio is 0.05%, and the loss factor of MWCNTs reinforced UHPC is 0.06003, which is consistent with the experimental value. In this paper, the MWCNTs slip-damping model by Glaz *et al.* is combined with the DMA test, double analysis showed that MWCNTs enhanced the damping performance of ultra-high performance concrete.

A schematic diagram of whether the CNT was pulled out and how the covalent bonds, mechanical interlocks, and van der Waals forces act is shown in Figure 9. When UHPC was molded, MWCNTs and the matrix interact with each other through a combination of covalent bonds, mechanical interlocking on the structure, and van der Waals force. When an external force was applied to the UHPC, the interface between the MWCNTs and the substrate remained unchanged at the beginning. The initial bonding and interaction force between MWCNTs and the substrate were destroyed until the critical shear stress was reached. The breakage of covalent bonds was irreversible, while mechanical interlocking and van der Waals force were reversible, which formed a “stick” mechanism. Under dynamic loading, mechanical interlocking and van der Waals forces were repeatedly reconstructed and destroyed, and the interface between MWCNTs and substrate was always sliding, which was called friction-slip energy dissipation system [33, 35].

Figure 9: (a) Unpulled out CNT and the bonding mode between MWCNTs and matrix; (b) CNT be pulled out

3.3 The microstructure of MWCNTs reinforced UHPC

The internal morphology of MWCNTs reinforced UHPC with different amounts of MWCNTs is shown in Figure 10 after curing for 28 days. Figure 10 (a) (b) show a CNT with one end fixed and one end free at that crack, which could be considered as a strain on the substrate when the force applied exceeded the bonding force between the CNT and the substrate, one end of the CNT was pulled out, and a large specific surface area of the CNT was rubbed against the substrate. Moreover, free MWCNTs can rub against each other, which increased the energy dissipation capacity again. As can be seen from Figure 10 (c) (d), that MWCNTs were embedded inside the cement matrix, could be effectively and tightly bonded with the cement matrix, had a thin interface transition region, and could be effectively transmitted to the MWCNTs when the matrix was stressed. The mechanical interlocking and van der Waals force on the structure will lead to the debonding of the CNT and the matrix, resulting in friction slippage and micro-cracks in the UHPC matrix. At this time, the bridging effect of the CNT at the cracks can be brought into full play and the development of the cracks can be restrained, as shown in Figure 10 (e) (f). The mechanical interlocking and van der Waals force on the structure would lead to the debonding of the MWCNTs and the matrix, resulting in friction slip-

Figure 10: The microstructure of CNT-reinforced UHPC after curing for 28 days: (a) (b) CNT tightly bonded to the matrix (c) (d) CNT with one end fixed and one end free (e) (f) bridging of CNT (g) (h) CNT agglomerated in the substrate

page and micro-cracks in the UHPC matrix. At this time, the bridging effect of the MWCNTs at the cracks could be brought into full play and the development of the cracks could be restrained, as shown in Figure 10 (e) (f). These two processes consume a great deal of energy, so the damping property of the matrix is improved. When the MWCNTs were not completely pulled out, the MWCNTs first overcome the covalent bond, mechanical interlocking, and van der Waals force under periodic dynamic oscillation force, then returned along the previous trajectory under reverse loading force, and the mechanical interlocking and van der Waals force formed a cycle again. As long as the periodic force existed, MWCNTs would continue to dissipate energy and form a friction energy dissipation system in the process of repeatedly being pulled out and pushed back.

Figure 10 (g) (h) show the phenomenon that MWCNTs were too much to be dispersed and agglomerated. When the amount of MWCNTs was too much, it would be absorbed by each other because of van der Waals force and agglomeration would occur. Because of the low water binder ratio of UHPC, a large number of MWCNTs could not be effectively dispersed in a small amount of water, and the agglomerated MWCNTs were loosely wound together without bonding with the cement matrix, forming a large number of interfaces in the same region, which would form defect sites in UHPC and play the role of crack initiation. Because of agglomeration, a large number of MWCNTs were not bonded to the matrix, and the bridging and energy dissipation of MWCNTs were greatly weakened, which lead to the decrease of the mechanical properties and damping properties of the composites.

4 Discussion

According to the results of TFE-SEM, the agglomeration of MWCNTs was a major factor affecting the mechanical and damping properties of MWCNTs reinforced UHPC. Because of the transverse expansion and cracking of the cement specimens under compression, most of the MWCNTs were in compression state because of the small size and limited incorporation of MWCNTs, and do not play a bridging role in the cracks, so the increment of the compressive strength of UHPC was limited. However, the content of MWCNTs and the effectiveness of MWCNTs dispersion became the key factor of flexural strength. The flexural strength of MWCNTs reinforced UHPC depended on the bridging action of MWCNTs, and the bridging action is highly dependent on the effectiveness of MWCNTs dispersion in the matrix. Effective dispersion could make MWC-

NTs well distributed in the hydrates of the C-S-H phase, and the effective bonding with the matrix enhances the bridging effect of MWCNTs. When the amount of MWCNTs in the cracks far exceeded the compressive state, the effective ratio increases greatly, so the flexural strength of UHPC was greatly enhanced. When the amount of MWCNTs was too much, a small amount of water could not effectively disperse the large amount of MWCNTs, which will lead to the aggregation effect caused by van der Waals force, forming defect sites in the interior of UHPC, and finally leading to the decline of flexural strength of UHPC.

The MWCNTs used in this study are MWCNTs, which was composed of several concentric tubes. When UHPC was subjected to external force, the internal friction of several concentric tubes in MWCNTs began to occur. When the external force continues to increase until it exceeded the critical point of slip between MWCNTs and cement matrix, MWCNTs began to frictional slip, which included the slip between different MWCNTs and the slip between MWCNTs and cement matrix. The energy dissipation was realized by converting mechanical energy into thermal energy, which leads to the increment of damping property. The continuous increase of strain leads to the gradual loss of energy storage modulus and the cumulative damage between MWCNTs and matrix. The nature of the damage may be the debonding between MWCNTs and matrix, and the stress in the matrix could not transfer to MWCNTs effectively, so the strengthening effect was lost. The results of TFE-SEM showed that the large area zigzag adhesion of cement-based materials along the surface of MWCNTs will result in mechanical interlocking, which may contribute to the vibration reduction effect of cement paste. Besides, the occlusion of MWCNTs with the hydrated product will lead to a stress concentration around the reinforcement region, which was beneficial to the disconnection of the weak links.

5 Conclusions

In this paper, the results of mechanical properties and damping properties of MWCNTs reinforced Ultra-high performance concrete with different content of MWCNTs are presented. The conclusions of this study are summarized as follows:

- (1) When the content of MWCNTs in UHPC was 0.03%, 0.05% and 0.07%, the compressive strength of UHPC was increased by 1.4%, 2.7%, and 2.1% respectively compared with reference sample without MWCNTs.

- (2) The flexural strength of UHPC was significantly improved by the addition of MWCNTs. The flexural strength of UHPC contained 0.03%, 0.05% and 0.07% of MWCNTs was increased 51%, 68%, and 43% higher than that of reference sample, respectively.
- (3) The loss factors of 0.03% and 0.05% MWCNTs were 89.1% and 98.3% higher than those of the specimens without MWCNTs, respectively. However, the loss factor of the specimens with 0.07% MWCNTs is only 15.5% higher than that of the specimens without MWCNTs.
- (4) Multi-walled carbon nanotubes (MWCNTs) can improve the mechanical properties of UHPC as well as the damping property.

Acknowledgement: This research was financially supported by the National Natural Science Foundation of China (51678309, 51978339), Natural Science Foundation of Jiangsu Province of China (BK20161529), State Key Laboratory of Silicate Materials for Architectures (Wuhan University of Technology), Priority Academic Program Development Jiangsu Higher Education Institutions (PDPA). Thanks Dr Su Fan and Dr Yang Jing of Advanced analysis and testing center of Nanjing Forestry University for the help of the SEM and XRD tests.

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