Effects of Carbon Nanotubes on the Properties of Lightweight Concrete Prepared With Expanded Glass and Hydrophobic Silica Aerogel

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Abstract

This study aimed to study the effect of carbon nanotubes on the properties of expanded glass and silica aerogel based lightweight aggregate concrete. CNTs were dispersed in the polycarboxylate superplasticizer added water by ultrasonication energy for 3 minutes. Combinations of expanded glass (55%) and hydrophobic silica aerogel particles (45%) were used as lightweight aggregates. Study results show that the incorporation of MWCNTs significantly influences the mechanical and microstructural performance of aerogel based lightweight concrete. Almost 41% improvement in compressive strength was gained by the addition of carbon nanotubes. SEM image of lightweight concrete shows CNTs were almost dispersed homogeneously within the concrete structure. SEM image of the composite also shows the presence of the C-S-H structure surrounding the CNTs, that confirms the cites of nanotubes for higher growth of C-S-H. Besides, agglomeration of CNTs and the presence of Ettringites observed in the transition zone between the silica aerogel and cementitious materials. Moreover, flowability, water absorption, microscopy, XRD, and semi-adiabatic calorimetry results were analyzed in this study.

1. Introduction

Nowadays utilization of carbon nanotubes in cementitious materials is getting attention for the improvement of physical and mechanical characteristics. Carbon nanotubes (CNTs) are an allotrope of carbon composed of covalent carbon rings and cylindrical in shape having around 132 000 000:1 length-diameter ratio. Carbon nanotubes are categorized into single-wall carbon nanotube (SWCNT) and multiwall carbon nanotube (MWCNT). Due to nanoscale diameters and its smooth surfaces, the early age hydration of cementitious materials could be affected [1]. Moreover, due to its physical properties, small doses of MWCNT can effectively improve the mechanical properties of cementitious composites by slightly influencing the hydration time and flowability [2,3]. The reinforcing efficiency of carbon nanotubes can be influenced by several parameters such as type of CNTs[4], the concentration of CNT [5], dispersion surfactants [6], treatment of CNTs[3,7], dispersion technique[8], the interaction with cementitious materials and bond strength [9], the water-cement ratio[10,11] and geometry of CNTs [12,13]. Zou, Bo, et al.[3] and Collins, Frank, et al.[10]reported in their study that ultrasonication energy and polycarboxylate based superplasticizer can significantly influence the mechanical and microstructural properties of CNT incorporated cementitious composites by optimally dispersing the CNTs within a concrete structure. Han, Baoguo, et al. [14] reported that polycarboxylate based superplasticizer plays a double dispersion mechanism to disperse the cement and CNTs within the composite. Without proper dispersion technique agglomeration of CNTs can be noticed in the concrete structure due to the strong van der Waals forces and can influence the mechanical and microstructural properties. The improvement of cementitious composites found to be different for cement mortar, cement paste, and concrete. The highest improvement in compressive and flexural strength was observed 83.33% [15] and 30% [16] for cement paste; ~35% [4] and 28.04% [17] for mortar; and 38.62% and 38.63% for concrete [18], respectively. The strength development of cementitious composite also depends on the properties of aggregates and used pozzolanic materials. Expanded glass aggregates and silica aerogel is much lighter than the conventionally used normal weight aggregates. Besides that, the strength properties of lightweight aggregates are also much lower than the conventional normal weight aggregates, and due to this fact cement composites achieve lower mechanical properties and densities utilizing those lightweight aggregates. Mechanical properties of lightweight aggregate concrete also depend on the desired density of the composite, by decreasing the density mechanical properties decreases. Kuprińska et al. [19,20] reported the importance of grading of lightweight aggregates, an optimal grading of lightweight aggregates can reduce the porosity of lightweight aggregate concrete and improve mechanical performance. Yousefi, Ali, et al. [21] reported 39.02% enhancement in compressive strength of expanded glass aggregates using nanomaterials (Nano Titanium Dioxide). Hydrophobic silica aerogel is also a very lightweight and brittle material. Several studies reported a decrease in mechanical performance by utilizing silica aerogel [22,23]. Moreover, hydrophobic silica aerogel has lower adhesive properties with water-rich cementitious materials. Several researchers observed the separation gaps between the aerogel and cementitious materials in the transition zone [24,25]. While CNT is well-known materials for improving mechanical performance and cracks bridging mechanism [26]. The incorporation of CNT not only bridges the cracks and voids it can also change the microstructure of hydration products. Singh et al. [27] identified new compounds by X-ray Powder Diffraction analysis method due to the chemical bonds between the hydrates and carbon nanotubes. CNTs, also provide sites for the growth of C-S-H, and CNT can coat the calcium silicate hydrate and provide a larger contact area between the hydration product and CNT. As a result, stronger bonds are created between them which significantly helps to improve the mechanical properties of cementitious composites [28].

In this study, several lightweight concrete samples were prepared with different doses of CNTs. Expanded glass aggregates and hydrophobic silica aerogel used as lightweight aggregates. Microscopy of the composite deeply analyzed, especially surrounding the hydrophobic aerogel particles. The study was aimed to improve the mechanical performance of aerogel concrete by reducing the separation gaps between silica aerogel and cementitious materials. Moreover, fluidity, water absorption, and XRD analysis were carried out to investigate the influences of CNTs on the properties of aerogel incorporated cementitious composites.

2. Experimental Details

2.1. Materials Used in CNT-LWAC

For the preparation of lightweight concrete specimens EN 197-1:2011[29] standard requirements satisfied ordinary Portland cement of grade CEM I 42.4R and 50 μm size (average particle size) zeolite powder was used as binding materials. A total of 500 kg/m³ binding materials were used to prepare lightweight concrete samples, where 90% volume consists of cement, and 10% consists of zeolite. The chemical composition of cement and zeolite showed in Table 1. EN 13055 - 1:2002+AC:2004 [30] standard satisfying combinations of four different sizes of expanded glass aggregates, and 1-2 mm size irregular shaped hydrophobic silica aerogel particles holding the approval No. Z -3.212-1948 from the German Institute of Construction Technology (DIBt) were used as lightweight aggregates. 45% volume of total aggregates consist of silica aerogel having 70kg/m³ bulk density while the rest of 55% of aggregate contains a combination of 1-2 mm, 0.5-1 mm, 0.25-0.50 mm, and 0.1-0.3 mm size expanded glass aggregates. The physical properties of expanded glass aggregates showed in Table 2. MasterGlenium SKY 8700 polycarboxylate ether polymer-based superplasticizer (1.8% of cement mass) and MasterMatrix SDC 100 (0.3%
of cement mass) stabilizer were used as chemical admixtures. Multiwall-carbon nanotubes (MWCNTs) were used as nanofibers to enhance the mechanical performance of the lightweight aggregate concrete. The properties of MWCNTs showed in Table 3.

2.2. Dispersion of CNTs and specimen preparation

The dispersion of carbon nanotubes in the cement matrix is more challenging than in the conventional concrete mixture. Due to the reliable van der Waals forces between carbon nanotubes, the separations of aggregated carbon nanotube bundles are necessary to protect from defects in cement composites. In this study, carbon nanotubes were sonicated separately in water by ultrasonication energy (sonicated in 40% of total water content) with polycarboxylate based superplasticizer for 3 min. After mixing all mixing lightweight concrete mixing composition with 60% total water, sonicated carbon nanotubes liquid added to the concrete mixture and manually mixed for another 5 minutes. After the final mixing process, the flowability test was carried out and concrete samples were molded into 16.0×4.0×4.0 cm size prisms and kept at room temperature for 24 hours for the hardening process. After the setting process concrete samples were demolded and kept immersed in water until the 28th day of the hydration process in the climatic chamber having more than 95% RH and 20±1 °C temperature. The mixing composition of the lightweight concrete samples is shown in Table 4.

2.3. Flowability Test

The flowability of the CNT-LWAC was performed by flow table test satisfying EN 12350-5:2009 [31] standard requirements. For each type of concrete specimen, three times a flow table test was performed, and the mean value was taken as a result.

2.4. Compressive strength test

Compressive of CNT-LWAC was measured on the 28th day of the curing process satisfying requirements of EN 196 - 1:2016 [39] standard. The mean value of three specimens was taken as a result of each type of concrete sample.

2.5 Water absorption test

Water absorptions kinetics observation of the lightweight aggregate concrete specimens reveals the increase in the rate of water absorption on the 28 days of hydration. LWAC specimens were oven-dried at 105°C after the 28 days of hydration and immersed in water for 15 min, 1 h, 24 h, and 48 h for the observation of water absorption of the LWAC specimens.

2.6. Semi-adiabatic calorimetry test

To perform a semi-adiabatic calorimetry test several mortar samples were prepared with cement and aerogel containing different concentrations of CNTs. CNTs were sonicated in water for 3 minutes before mixing with the cement. Table 5 shows the mixing composition of cement paste.

2.7. Scanning electronic microscopy test

Scanning electronic microscopy of CNT-LWAC was analyzed by a high-resolution electronic microscope FEI Quanta 200 FEG with Schottky field emission gun (FEG), an energy-dispersive X-ray spectrometer (EDS) with a silicon type drift droplet detector.

2.8 X-ray diffraction

The X-ray diffraction analysis of the composite specimens was performed with X-ray diffractometer DRON-6 with Bragg-Brentano geometry using Ni -filtered Cu Kα radiation and graphite monochromator, operating with the voltage of 30 kV and emission current of 20 mA. The step-scan was performed from the angular range 2°–70° (2θ) and each step of 2θ was 0.02°.

3. Results And Discussion

3.1. Flowability test of CNT-LWAC

The flowability of CNT added cementitious composites depends on several parameters like ultrasonication energy [8], treatment of CNTs [32], the water-cement ratio [33], the concentration of CNTs [34], and type of fine fillers [35]. Mostly studied literature [10,34,36,37] illustrates that the incorporation of CNTs reduced the flowability of cementitious composites. While several studies also indicate the increase in flowability of CNT incorporated cementitious composites [38,35,32]. Besides, the incorporation of silica aerogel also reduces the flowability of cementitious composites [25]. However, this study results revealed that the flowability of CNT-LWAC was influenced by the quantity of CNT. The flowability of CNT-LWAC decreases with the escalating doses of CNTs. Almost a 17% reduction in flowability was measured for lightweight concrete specimen prepared with 0.6 wt% CNT. The flowability of CNT-LWAC specimens was shown in Figure 1. The possible reason for the reduction in flowability can be associated with agglomeration and strong van der Waals forces of CNTs. A higher duration of ultrasonication energy can improve the dispersion of CNTs within the concrete and reduce the agglomeration and strong van der Waals forces. Higher doses of superplasticizer can adjust the flowability of the concrete. Moreover, due to the high specific gravity of CNTs, a large amount of superplasticizer is required to overcome the intermolecular forces. Besides, nanoparticles enhance the packing density of concrete by filling up the micro and mesopores which significantly influence the demand of superplasticizer [26].

3.2. Semi-adiabatic calorimetry test of CNT- LWAC

Figure 2 demonstrates the semi-adiabatic temperature rise of CNT incorporated cement mortar. Study results revealed that by incorporation of silica aerogel setting time of the cement mortar was slightly retarded and produced lower heat of hydration than the plain cement mortar. Study results confirm the
reactivity of silica aerogel with cementitious materials. Similar phenomena were noticed in the previous study [25]. While the addition of CNTs to the aerogel adding cement paste SA-2 and SA-3 shows slightly higher produced heat and shortened setting time than the sample SA-2. Besides, by increasing the concentration of CNTs slightly higher produced heat of the exothermic reaction was noticed.

### 3.3. Strength of CNT-LWAC

Figure 3 shows the compressive strength of the control sample was measured at 5.4 MPa. Study results show that the addition of CNT to the lightweight concrete CNT significantly influences the mechanical. By the increase in the concentration of CNTs the compressive strength was gradually increasing. However, the sonicated LWAC specimens showed better improvement in compressive strength against the control concrete sample. The compressive strength of the sonicated concrete specimens was increasing by the increasing doses of CNTs. The highest improvement in compressive strength was measured at 41.48% for AS-6 containing 0.60 wt% CNT. The relative increase in compressive strength of CNT-LWAC portrait in Figure 4. Aerogel is well known lightweight fragile material, and literature confirms the reduction in the mechanical performance of aerogel incorporated cementitious composites [40,41,42]. Incorporation of small doses of CNTs to the aerogel based lightweight concrete significantly increase in compressive strength was noticed. Similarly, an increase in compressive strength phenomena was identified by Xu, Shiliang et al. [43]. The increase in compressive strength can be attributed to the nucleating effects and improvement of the microstructure of CNT-LWAC. The structure of C-S-H was identified surrounding to the CNTs. Moreover, hydration products and CNTs were filling the micro crack/gaps of the lightweight concrete that can provide additional support and helps to increase compressive strength. Detailed descriptions were discussed in 3.5 paragraphs. Besides, literature studies confirm that conforms incorporation of nanoparticles improves the microstructure and provide a denser concrete structure[26]. A decrease in water absorption of the CNT-LWAC confirms the denser structure of CNT-LWAC.

### 3.4. Water absorption

Figure 5 illustrates the water absorption kinetics of the CNT-LWAC specimens containing up to 0.60 wt% CNTs. Water absorption rate of control sample was measured 14.98%, 22.74%, 32.33% and 34.33% at 15 min, 1 hr, 24 hr and 48 hr that decreased to 13.20%, 16.31%, 28.86% and 30.42% respectively. Madhavi, T. Ch, et al. [44], and Leonavičius, Dainius, et al. [45] reported that at a lower concentration of CNTs total pore volume reduced by filling the voids and leads to a reduction in water absorption. Moreover, a high concentration of CNTs in concrete leads to a more porous structure and reduces the mechanical performance of concrete [45,46]. In our study, all nanocomposite concrete specimens show a small decrease in water absorption rate by an increase in the concentration of CNTs. The reduction in water absorption can be attributed to the association of CNTs to the lightweight concrete that helps decrease the micropores and produce the denser concrete structure. Besides, a comparatively higher water absorption rate was observed than Leonavičius et al. [45] and Kordkhelli et al. [46] due to the uses of expanded glass aggregates in the study. Expanded glass aggregates are porous in structure and contain several pores that can absorb water up to 20 to 25% which attributes the increases in water absorption.

### 3.5. Scanning electronic microscopy (SEM) of CNT-LWAC

The plain image of hydrophobic silica aerogel in Figure 6 (a) suggested that it is a very brittle material having cracks on the surface. Which can easily break into pieces during the mixing process and leads to achieving lower mechanical properties. Moreover, in few aerogel particles, the cracked surface of aerogel in the hydrated concrete specimens was noticed (Figure 6 b). Literatures [25,47,48] also indicate the brittleness of aerogel, and the incorporation of aerogel decreases the mechanical performances.

Due to the hydrophobic nature of silica aerogel, it has no chemical bonds with the hydrophilic cement matrix. Figure 7 (a) clearly shows the separation gaps between aerogel and surrounding cementitious material in the transition zone (control sample). This phenomenon indicates the lower adhesion properties of hydrophobic silica aerogel. Similar separation gaps were identified by [24,25]. While better adhesion was observed for expanded glass aggregates with cementitious materials (Figure 7 b). Through the separation gaps, air and/or water can easily transport and makes concrete weaker. Interestingly the separation gaps were reduced by utilizing carbon nanotubes (Figure 8). Separation gaps between hydrophobic silica aerogel and surrounding cement-based materials were filled by hydration products and CNTs.

SEM image Figure 9 of CNT-LWAC also shows the CNTs were almost dispersed uniformly within the concrete structure. At the high concentration of CNTs, a network-like distribution within the composite structure was noticed. Zou, Bo, et al.[8], Vesmawala, Gaurang R., et al.[6] and Collins, Frank, et al.[10] also reported that CNTs can be effectively dispersed within the concrete structure by ultrasonication energy and polycarboxylate superplasticizer may be due to this fact high agglomeration of CNTs wasn’t noticed. Unlikely, needle-like structure of ettringite was observed along with the agglomeration of CNTs in the transition zone of aerogel (Figure 8). However, increasing the duration of ultrasonication and concentration of superplasticizer can effectively help to improve the dispersion of CNTs without agglomeration. Moreover, CNTs were found to reinforcing the micropores of the concrete structure Figure 10.

Pinghua Zhu et al. [42] suggested that due to the hydration process of cementitious materials aerogel particles can slightly react with the pore solution and partially dissolved in an alkaline environment and form C-S-H with a low Ca/ Si ratio. de Fátima Júlio, Maria, et al. [49] and Hai-Il, Cheng, et al.[50] reported that aerogel particles can promote hydration due to high surface activity and ASR can take place and Si-O-Si might form C-S-H. Incorporation of CNTs to the cement composite also provides sites for the formation of calcium silicate hydrate (C-S-H) by acting as a nucleating agent [51,43]. The honeycomb structure of C-S-H and presence of C-S-H nearly to the CNTs can easily be observed in Figure 8 (a), Figure 9 (b), that illustrates the nucleating effects of CNTs.

### 3.6. X-ray diffraction analysis of CNT-LWAC

Figure 11, Figure 12, Figure 13, and Figure 14 show the X-ray diffraction analysis of expanded glass aggregates, silica aerogel, Portland cement, and LWAC specimens (control, AS-1, AS-3, and AS-6). X-ray diffraction pattern of silica aerogel reveals the amorphous nature of silica aerogel. A broad peak without any narrow peak in the range of 20°–30° were identified. X-ray diffraction pattern of CNT-LWAC concrete specimen illustrates that the intensity of portlandite near
about 34° and 47° increases with the increasing concentration of CNT. The increasing peak of calcium silicate hydrate near 29°, 32°, and 50° explained the nucleation effects of carbon nanotubes. Moreover, CNT-LWAC shows a slightly higher amount of calcite and ettringite than the control specimen. However, A higher amount of hydration products was observed for CNT incorporated LWAC specimens. A higher concentration of CNTs within the concrete structure leads to higher growth of hydration products. The similar increasing peak of hydration products by incorporating CNT in the cementitious composite was identified by El-Gamal et al. [52].

4. Conclusion

Study results analyses the viability of using MWCNTs to improve the mechanical performance of lightweight aggregate concrete prepared by silica aerogel and expanded glass aggregates. The following conclusions can be drawn based on the obtained results.

- The Flowability of CNTLWAC was decreased by increasing the concentration of CNTs. At 0.6 wt% of CNT loading, an almost 17% reduction in flowability was measured for the lightweight concrete specimen.
- The Utilisation of CNTs significantly improves the mechanical performance of the aerogel added lightweight concrete. Almost 41% improvement in compressive of lightweight concrete was observed at 0.6 wt% CNTs loading.
- The dispersion technique of CNTs by sonication with water and polycarboxylate based superplasticizer works almost effectively to disperse the CNTs within the concrete structure. Some agglomerations were identified in the transition zone of aerogel.
- CNTs were found to promote the growth of C-S-H, portlandite, and calcite. More hydration products were identified surrounding to the CNTs.
- Separation gaps were identified in the transition zone between the hydrophobic silica aerogel and cementitious materials for the control specimen. The utilization of CNTs effectively helps to reduce the separation gaps by filling the voids and gaps. Moreover, the nucleating effects of CNTs were noticed, separations gaps and voids were not only filled by CNTs, hydration products were also found in the gaps.

5. References


**Tables**

**Table 1. Chemical properties of cement and zeolite**

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>Na₂O eq</th>
<th>SO₃</th>
<th>Cl</th>
<th>TiO₂</th>
<th>LOI</th>
<th>Insoluble residue</th>
<th>Free Lime</th>
<th>Lime stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement</td>
<td>63</td>
<td>20.4</td>
<td>4.1</td>
<td>3.5</td>
<td>2.9</td>
<td>0.7</td>
<td>0.23</td>
<td>0.74</td>
<td>3.2</td>
<td>0.03</td>
<td>-</td>
<td>2.5</td>
<td>0.5</td>
<td>1.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Zeolite</td>
<td>2.8</td>
<td>58.7</td>
<td>9.0</td>
<td>1.4</td>
<td>0.7</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.2</td>
<td>5.1</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

**Table 2. Physical properties of expanded glass aggregates**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Standard</th>
<th>Expanded glass aggregate size</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>0.1-0.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>Bulk density in kg/m³</td>
<td>EN 1097-3</td>
<td></td>
</tr>
<tr>
<td>Compressive strength (±15%)</td>
<td>EN 13055-1, A annex</td>
<td>2.8</td>
</tr>
<tr>
<td>Thermal conductivity in W/(m-k) (±0.02)</td>
<td>EN 12939:2002, A annex</td>
<td>0.0767</td>
</tr>
<tr>
<td>WATER absorption % by mass (absorption % after 24 hours submerged in water)</td>
<td>EN 1097-6:2002, C annex</td>
<td>25</td>
</tr>
<tr>
<td>Specific density</td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>pH value</td>
<td></td>
<td>9-11</td>
</tr>
<tr>
<td>Softening point</td>
<td></td>
<td>700°C/1300°F (approximately)</td>
</tr>
<tr>
<td>Color</td>
<td></td>
<td>Cream white</td>
</tr>
</tbody>
</table>

**Table 3. Properties of multiwalled carbon nanotubes (MWCNTs)**

<table>
<thead>
<tr>
<th>Material type</th>
<th>Appearance</th>
<th>Purity</th>
<th>Inner diameter</th>
<th>Outer diameter</th>
<th>Length</th>
<th>Specific surface area</th>
<th>Density</th>
<th>Actual density</th>
<th>Resistivity</th>
<th>Preparation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWCNT</td>
<td>Black powder</td>
<td>95wt%</td>
<td>3-5nm</td>
<td>8-15nm</td>
<td>3-12μm</td>
<td>233m²/g</td>
<td>0.15g/cm³</td>
<td>2.1g/cm³</td>
<td>1412 μΩm</td>
<td>CVD</td>
</tr>
</tbody>
</table>

**Table 4. Mixing composition of lightweight concrete samples, Materials for 1 m³ of concrete**
Table 5. Mixing composition of CNT-cement paste for the semi-adiabatic calorimetry test.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cement, g</th>
<th>CNT, g</th>
<th>Water, g</th>
<th>Aerogel, g</th>
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</thead>
<tbody>
<tr>
<td>SA-1</td>
<td>100</td>
<td>-</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>SA-2</td>
<td>100</td>
<td>0.04</td>
<td>35</td>
<td>31.5</td>
</tr>
<tr>
<td>SA-3</td>
<td>100</td>
<td>0.15</td>
<td>35</td>
<td>31.5</td>
</tr>
<tr>
<td>SA-4</td>
<td>100</td>
<td>0.45</td>
<td>35</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Figures

**Figure 1**
Flowability of sonicated CNT-LWAC specimens.
Figure 2

Hydration of cement mortar containing aerogel and sonicated and un-sonicated CNTs.

Figure 2

Hydration of cement mortar containing aerogel and sonicated and un-sonicated CNTs.
Figure 3
Compressive strength of sonicated CNT-LWAC specimens.

Figure 4
Relative increase/decrease in compressive strength of un-sonicated CNT-LWAC specimens.

Figure 5
Water absorption of sonicated CNT-LWAC specimen.

Figure 6
(a) Cracks on the surface of native silica aerogel; (b) cracks aerogel in the hydrated concrete specimen.

Figure 7
(a) Separation gaps between aerogel and cementitious material in the transition zone, (b) good adhesion of expanded glass aggregates with cementitious composites.
Figure 8
Agglomeration of CNTs and presence of ettringite and honeycomb structure of C-S-H in the transition zone of aerogel and cementitious material.

Figure 9
The well-dispersed concrete sample under high concentration of CNT at different magnification; the presence of C-S-H structure surrounding to the CNTs.
Figure 10

CNTs filling the micropores of the lightweight concrete structure.

Figure 11

X-ray diffraction pattern of expanded glass aggregates.
Figure 12

X-ray diffraction pattern of silica aerogel.

Figure 13

X-ray diffraction pattern of Portland cement. Notes: A—alite Ca$_{54}$MgAl$_2$Si$_{16}$O$_{90}$ (13-272); B—brownmillerite Ca$_2$ (Al, Fe)$_2$ O$_5$ (30-226); L—belite Ca$_2$SiO$_4$ (33-302).
Figure 14

X-ray diffraction pattern of sonicated CNT-LWAC specimens. Notes: A – alite Ca₅₄MgAl₂Si₁₆O₉₀ (13-272); E – ettringite Ca₆Al₂(SO₄)₃(OH)₁₂·26H₂O (41-1451); L – Ca₂SiO₄ belite (33-302); K – Ca₁.₅Si₀₃.₅·ₓ H₂O calcium silicate hydrate (33-306), Cc – Ca(CO)₃ calcite (24-27); P – Ca(OH)₂ portlandite (1-837).