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Hybrid effect of carbon nanotubes and silica aerogel on mechanical, durability, and thermal properties of concrete

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Abstract:

Silica aerogel improves the thermal insulation of concrete but typically reduces its compressive strength. Carbon nanotubes (CNTs) were incorporated to compensate for this strength loss. Sixteen concrete mixtures containing 0–8% silica aerogel (by volume) and 0–0.5% CNTs (by weight of cement) were tested for compressive strength, electrical resistivity, chloride ion penetration, and heat transfer coefficient. **Results**. The results demonstrate that the hybrid combination of CNTs and silica aerogel simultaneously enhances durability, mechanical strength, and thermal insulation. The optimal mixture (0.3% CNTs + 4% silica aerogel) increased 28-day compressive strength by 21% and reduced the heat transfer coefficient by 73% relative to control concrete. The highest compressive strength (58 MPa, 35% increase) was recorded for 0.3% CNTs with 6% silica aerogel, while the lowest thermal conductivity (0.451 W/m·K) was achieved with 0.2% CNTs and 8% silica aerogel. CNTs effectively mitigated the aerogel-induced increase in porosity and chloride ion permeability, producing a high-performance concrete suitable for energy-efficient construction.

1 Introduction

Due to the widespread use of concrete in various structures and problems such as high structural weight, energy loss, and short service life under environmental conditions, improving the physical and mechanical characteristics of concrete is of great importance [1]-[3]. For lightweight and mass construction in the building industry, having adequate thermal insulation properties is essential. One approach to address this issue is adding silica aerogel to concrete mixtures [4]. The benefits of silica aerogel include high insulation properties and reduced weight of concrete structures. However, adding this material in large quantities leads to a significant decrease in concrete strength [4]-[6].

Previous studies have shown that using silica aerogel up to 63% of concrete volume reduces the heat transfer coefficient from 1.8 to 0.3 W/m·K, but decreases compressive strength on average. Furthermore, research has demonstrated that increasing silica aerogel content increases porosity and permeability of concrete [7]. On the other hand, carbon nanotubes (CNTs) have high potential to improve concrete strength and durability due to their unique properties. Studies have shown that adding CNTs up to 0.05% by weight of cement can improve strength and heat transfer, and reduce permeability while creating a thermal insulation layer in foam concrete [8],[9].

Despite extensive research on the individual use of silica aerogel and carbon nanotubes in concrete, a significant scientific gap exists: the combined effects of these two materials on the mechanical, durability, and thermal properties of concrete have not been systematically investigated. In other words, it is unclear whether carbon nanotubes can compensate for the loss of strength and durability caused by silica aerogel while maintaining desirable thermal insulation. Moreover, no study has determined the optimal dosages of these two materials to achieve a balance between strength, durability, and insulation [10], [11].

Therefore, the research topic is the investigation of the simultaneous effects of carbon nanotubes and silica aerogel on concrete properties. The main objective is to obtain a concrete mix design that possesses adequate compressive strength and durability while having the lowest heat transfer coefficient (highest thermal insulation) [12]. The specific objectives of the study are:

1. To determine the effects of different dosages of silica aerogel (0, 4, 6, 8% by volume) and carbon nanotubes (0, 0.2, 0.3, 0.5% by weight of cement) on 7-day and 28-day compressive strength;
2. To evaluate concrete durability through measurements of electrical resistivity, chloride ion penetration, and permeable porosity;
3. To measure the heat transfer coefficient to determine thermal insulation efficiency;
4. To identify the optimal mix design that provides the best balance among mechanical, durability, and thermal properties.

By conducting this research, not only is the existing scientific gap addressed, but also a practical solution for producing lightweight, strong, and energy-efficient concrete is provided.

2 Materials and methods

2.1 Materials and mixing plans

To determine the compressive strength and heat transfer, concrete samples with a combination of cement, water, aggregate, silica aerogel, and carbon nanotubes were used. The carbon nanotube used in this research is multi-walled, 30 microns long, 10 nanometers in diameter, 95% pure, true density 2.1 grams per cubic centimeter, and with a specific contact surface of 200 m2/g. The carbon nanotubes used in this research are of an industrial functionalized type with hydroxyl agent (-OH) in the amount of 0.7% by weight of carbon nanotubes. In order to better mix, the aqueous solution containing functionalized carbon nanotubes was subjected to ultrasonic conditions for one hour. In this research, Portland cement with a grade of 360 kg/m3 was used. The water-to-cement ratio was 0.485, and the specifications of the aggregates used were ASTM C136 [13], ASTM C33 [14], and ASTM C778 [15]. The largest size of aggregate used was measured to be 12.5 mm.

Table 1. Specifications of the aggregate used

Name of aggregate	Sand	Pea gravel	Almond gravel
Water absorption percentage (%)	2.69	1.46	1.05
Specific weight	2670	2674	2674

In this research, 16 mixing plans were considered, and a total of 192 concrete samples were made, which included 96 cubic samples and 96 cylindrical samples. Cubic samples with dimensions of 15 cm and cylindrical samples with a diameter of 10 cm and a height of 5 cm were prepared. All the samples were processed in the same conditions and inside the city drinking water at a temperature of 22 degrees. Cubic samples were used for the 7-day and 28-day compressive strength test, and 28-day heat transfer coefficient test, and cylindrical samples were used to measure chloride ion penetration and 28-day specific resistance. The consumption amount of silica aerogel was considered to be 0, 4, 6, 8 percent by volume of concrete, and the amount of carbon nanotube consumption was considered to be 0, 0.2, 0.3, 0.5 percent by weight of cement. From each mixing plan, 3 cubic samples and 3 cylindrical samples were prepared to determine compressive strength, heat transfer coefficient, chloride ion penetration, and specific resistance. The studied mixing scheme is shown in Table 2.

Table 2. Mixing plans

The title of the project	Carbon nanotube	Silica aerogel	Sand	Gravel
	%	%	Kg/m3	Kg/m3
N	0	0	1200	675
CNT2	0.2	0	1200	675
CNT3	0.3	0	1200	675
CNT5	0.5	0	1200	675
AG4	0	4	1135	635

AG6	0	6	1103	616
AG8	0	8	1069	599
M24	0.2	4	1135	635
M34	0.3	4	1135	635
M54	0.5	4	1135	635
M26	0.2	6	1103	616
M36	0.3	6	1103	616
M56	0.5	6	1103	616
M28	0.2	8	1069	599
M38	0.3	8	1069	599
M58	0.5	8	1069	599

In order to spread carbon nanotubes in water better, an ultrasonic device was used. To make the samples, the concretes were entered into the molds in three stages, and a vibrating table was used to compact the concrete. Next, the concretes were covered with a damp towel for 24 hours inside the mold. Then the samples were removed from the mold and placed inside the water tank with a controlled temperature of 22 degrees Celsius for processing.

2.2 Compressive strength test of concrete

In this research, the test to determine the compressive strength of the samples was carried out according to EN 12390-3 standard. For this purpose, 3 samples of each mixing design were subjected to loading at the ages of 7 and 28 days, and their average was considered as the compressive strength of the desired design.

2.3 Durability test of concrete

In this research, in order to evaluate the durability of concrete, specific concrete strength tests, chloride ion permeability, and permeable porosity tests were used.

2.3.1 Specific strength test of concrete

The electrical resistance of concrete is one of its inherent properties, which depends on the moisture level of concrete and its compounds [16]. Information about the reliability of concrete can be obtained from the electrical resistance of concrete. Under the effect of an electric field, concrete acts like a capacitor along with resistance. By changing the frequency of the electric current, the real strength of concrete can be achieved. In this research, the two-point method was used to measure the electrical resistance of concrete by using two electrodes installed on the concrete surface and establishing an electrical connection and contact. In order to create better conductivity, copper sulfate gel was used, and the electric potential was measured based on the passage of alternating current between two electrodes. The electrical resistance device used was set based on a frequency of 2 kHz and the final capacity of 1 mega ohm. In the following, the specific strength of concrete was obtained through Equation 1. Corrosion risk based on electrical resistance is shown in Table 3.

$$\rho = \frac{RA}{L}, \tag{1}$$

where (ρ) is the resistivity, (R) is the resistance, (A) is the cross-sectional area of the sample, and (L) is the distance between the electrodes or the height of the sample.

Table 3. Corrosion risk criteria

Specific electrical resistance	Corrosion
< 5	too much
5 - 10	a lot
10 – 20	Medium to low
> 20	insignificant

2.3.2 Chloride ion permeability test

One of the main factors of premature failure in reinforced concrete structures is the corrosion of rebars, and the most important factor in increasing the speed of this destruction is the permeability of concrete [17]. On the other hand, there are different methods to evaluate the permeability of concrete. The electrical resistance of concrete is a suitable index to evaluate the permeability of concrete and its resistance to chloride ion penetration. This method is completely non-destructive, and its simplicity, speed and economy add to the use of this method. There are different methods to evaluate chloride ion penetration into concrete. There are limitations in methods that are only based on diffusion. Among these limitations is the long time required for chloride ion release to reach a steady state. Therefore, these methods are not practical for evaluating the resistance of concrete against chloride ion penetration. ASTM C1202 standard was used to quickly determine chloride ion penetration. In this method, both sides of a sample of fully saturated concrete cylinders with a diameter of 100 mm and a thickness of 50 mm are placed in solutions of sodium chloride and caustic soda of specified concentration.

An electric current is applied with a potential difference of 60 V, and the current intensity passing through the saturated concrete is obtained. Within 6 hours, the amount of current passing through the concrete is calculated in coulombs, which is an indication of the concrete's resistance to this current. The higher this flow rate, the greater the permeability of the concrete, especially to chloride ions [18].

2.3.3 Permeable pore testing

Permeable pores have an effect on the loading properties and durability of concrete and are related to many destructive processes of concrete (Safiuddin and Hiran, 2005). and then the mass of the samples is repeated with time steps of 24 hours until the mass reduction in these steps does not exceed 1%. Then the mass of the saturated sample with the dry surface (Ws) in it (Wd) and the mass of the saturated sample immersed in water (Wb) is measured. The amount of permeable concrete pores is determined from Equation 2.

$$\text{Permeable porosity} = \frac{w_s - w_d}{w_s - w_b}, \qquad (2)$$

2.4 Heat transfer test

Energy saving is one of the important issues in the construction industry. Proper thermal insulation is one of the ways to prevent energy loss. Nowadays, the use of insulating concrete is one of the effective methods in reducing energy loss and increasing the thermal safety of buildings. Thermal conductivity coefficient (thermal transfer coefficient) is one of the important parameters in choosing this type of concrete for insulation. In this research, the test to determine the heat transfer coefficient for cylindrical samples after 28 days of curing using a coefficient measuring device The heat transfer was measured with a sensor (Figure 1). The heat transfer coefficient for each mixture was taken as the average of 5 times of measurement with time intervals of one minute.

Fig. 1- Heat transfer coefficient measurement device
Image by the author of the article

3 Results and discussion

3.1 Effect of carbon nanotube and silica aerogel on compressive strength

The results of the 7 and 28-day compressive strength test of cubic samples with dimensions of 15x15x15 are presented in Table 4.

Table 4. Results of concrete compressive strength test

Mixing plan	7-day compressive strength	28-day compressive strength
N	27	43
CNT2	31	50
CNT3	35	55
CNT5	30	49
AG4	28	41
AG6	28	43
AG8	30	46
M24	32	47
M34	34	52
M54	32	50
M26	31	52
M36	36	58
M56	30	51
M28	32	52
M38	29	48
M58	30	49

According to the 7-day compressive strength results with different percentages and combinations of carbon nanotubes and silica aerogel presented in Table 4, it can be seen that the compressive strength values of all the mixtures have increased compared to the strength of the control sample. This issue can be interpreted in the way that the particles of nanotubes and silica aerogel have strengthened the cement paste by filling the empty spaces. Among the samples, the highest resistance is related to sample M56, which contains 0.5% by weight of carbon nanotubes and 6% by volume of silica aerogel. The 28-day compressive strength results have a similar trend to the 7-day results, and in the 28-day samples, the M36 sample shows the highest resistance, which is 35% more resistant than the control concrete. In the combination of nanotubes and silica aerogel, the highest percentage increase in 7-day strength compared to 28 days is when the amount of aerogel percentage is increased, which can be caused by the reduction of water drop and water exit from concrete due to the presence of silica aerogel and subsequently maintaining the state concrete paste and delay in its hardening. Based on Table 4, in the case of application without the combination of the above materials, it can be said that the effect of carbon nanotube on the compressive strength is greater than that of silica aerogel, and by combining these two materials, the compressive strength is improved.

3.2 Concrete durability test results

In this research, in order to check the durability of concrete, the results of specific electrical resistance, chloride ion permeability and permeable pores have been used. The results of the test to determine the specific electrical resistance of concrete samples of cylinders with a diameter of 10 and a height of 5 cm and with 28 days of curing are shown in Table 5. According to the results obtained from this experiment with different combinations of carbon nanotubes and silica aerogel, it can be seen that the specific electrical resistance values in all the mixing designs have changes compared to the specific electrical resistance of the control sample. Among the samples, the highest specific electrical resistance is related to sample M24, which contains 0.2% by weight of carbon nanotubes and 4% by volume of silica aerogel. Based on the corrosion criteria based on specific resistance and Table 5, adding each of carbon nanotube and silica aerogel materials up to a certain amount has a better effect in increasing the durability of concrete than the normal state, but the combination of these two materials has a better effect.

The chloride ion permeability test was performed as one of the concrete durability criteria on 28-day samples of cylinders with a diameter of 10 and a height of 5 cm, and the results are reported in Table 5. According to the results obtained from this experiment with different combinations and different percentages of carbon nanotubes and silica aerogel, it can be seen that the permeability values of chloride ions in all the mixing designs are different from the permeability of the control sample. Among the samples, the lowest chloride ion permeability is related to sample 34M, which contains 0.3% by weight of carbon nanotubes and 4% by volume of silica aerogel. According to Table 5, the increase of carbon nanotubes has a good effect in reducing the penetration of chloride ions, and with the increase of the amount of nanotubes, the permeability of chloride ions also decreases, which can be caused by the very fine structure of Nano particles.

Also, with an increase of more than 0.06% of silica aerogel, chloride ion permeability increases. But you should be careful in the combination of these two substances.

Table 5. Concrete durability test results

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Mixing plan	special resistance	Chloride ion permeability	Permeable pores
	Ω.m	Colomb	
N	50.37313	4692.91	11.93
CNT2	61.64384	3879.65	10.45
CNT3	54.43548	3639.67	9.22
CNT5	48.3871	3573.01	8.28
AG4	57.93991	3493.02	14.98
AG6	53.78486	4532.93	18.56
AG8	46.23288	6572.74	21.01
M24	79.41176	3319.70	23.42
M34	64.5933	2799.75	18.61
M54	59.73451	4426.27	7.96
M26	55.55556	5266.19	22.19
M36	54.96203	4519.59	18.44
M56	60.26786	5066.21	28.16
M28	53.72414	6932.71	33.7
M38	52.14961	7332.68	26.57
M58	54.43548	5999.46	22.76

The results of the concrete permeable pores test for samples of 28-day-old cylinders with a diameter of 10 and a height of 5 cm are presented in Table 5. According to the results obtained from these experiments with different compositions and percentages of carbon nanotubes and silica aerogel, it can be seen that with the increase in the amount of carbon nanotubes, the amount of permeable pores decreases, which can be related to the filling of concrete voids by Nano particles. But silica aerogel harms permeable pores and increases them. The lowest porosity permeability is related to sample M54, which contains 0.5% by weight of carbon nanotubes and 4% by volume of silica aerogel.

3.3. Concrete heat transfer test results

In order to determine the exact effect of carbon nanotube and silica aerogel on the heat transfer coefficient of concrete, 3 samples were used for each test. The test results of 28-day concrete heat transfer samples are shown in Figure 2.

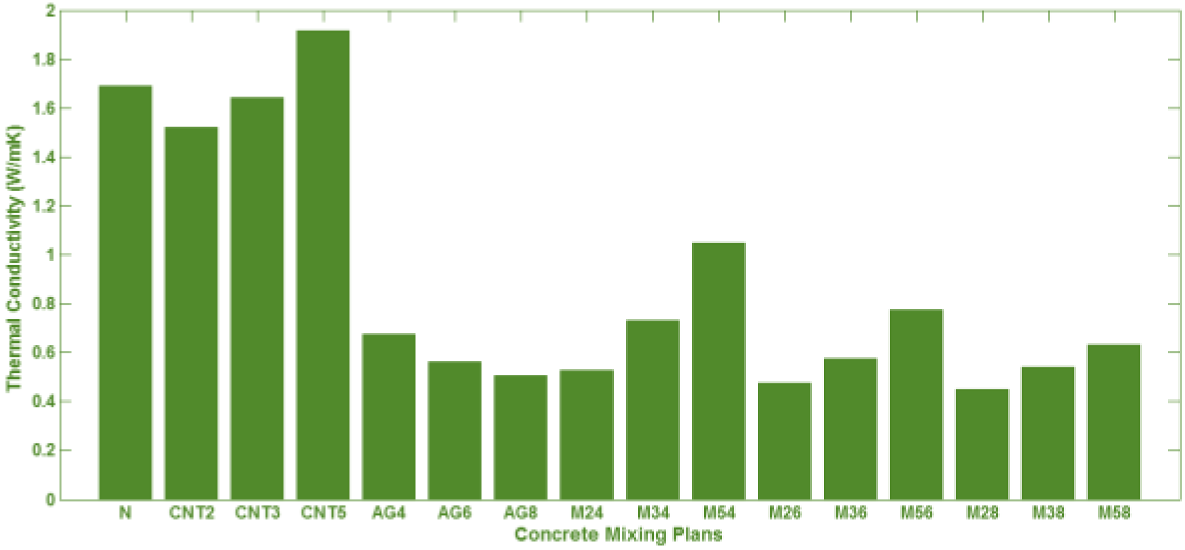

Fig. 2- Heat transfer values for all mixing modes
Image by the author of the article

Figure 2 shows that by adding carbon nanotube and silica aerogel materials, the heat transfer coefficient of concrete decreases compared to the control sample. Carbon nanotube particles alone in the mixing plan in amounts of more than 0.5% increase the heat transfer coefficient, which can be caused by the increase in conductivity in connection with cement paste. The biggest decrease in heat transfer coefficient is observed in all cases of using 8% silica aerogel. Among the mixtures performed, the lowest heat transfer rate is related to sample 28M which contains 0.2% by weight of carbon nanotubes and 8% by volume of silica aerogel, and its value was 0.451 W/m degrees Kelvin, which compared to the control sample has 73% decrease in the heat transfer coefficient compared to the control state. This mixing scheme is also true for the compressive strength of 28-day concrete.

Another research has been done by Benazuk et al. [19] and Farhan et al. [20] who respectively used recycled rubber powder, silica fume and rice husk ash to reduce the heat transfer coefficient of concrete. But they have caused a decrease in compressive strength and an increase in permeable pores in concrete.

4 Conclusion

In this research, to increase the resistance of concrete against heat transfer, carbon nanotubes and silica aerogel were used with the least reduction in the strength and durability of concrete. For this purpose, the results of tests of compressive strength, specific electrical resistance, chloride ion penetration and heat transfer coefficient were used. This study investigated the synergistic effects of carbon nanotubes (CNTs) and silica aerogel (SA) on the mechanical, durability, and thermal insulation properties of concrete. Based on the experimental results, the following conclusions were drawn:

1. Compressive Strength:
   - The addition of CNTs (up to 0.3% by weight of cement) significantly improved the compressive strength of concrete, with the M36 mix (0.3% CNT + 6% SA) achieving the highest 28-day strength (58 MPa), 35% higher than the control sample.
   - Silica aerogel alone reduced strength at higher dosages (e.g., 8% SA), but its combination with CNTs mitigated this effect, demonstrating that CNTs compensate for SA-induced strength loss.
2. Durability Performance:
   - Electrical Resistance: The M24 mix (0.2% CNT + 4% SA) exhibited the highest specific electrical resistance (79.4 Ω·m), indicating superior corrosion resistance.
   - Chloride Ion Penetration: The M34 mix (0.3% CNT + 4% SA) showed the lowest chloride permeability (2799 Coulombs), attributed to CNTs' pore-filling effect and SA's reduced connectivity of capillary pores.
   - Permeable Porosity: CNTs reduced porosity (e.g., 8.28% for CNT5), while SA increased it (21.01% for AG8). The M54 mix (0.5% CNT + 4% SA) achieved the lowest porosity (7.96%), highlighting CNTs' role in densifying the matrix.
3. Thermal Insulation:
   - The M28 mix (0.2% CNT + 8% SA) yielded the lowest heat transfer coefficient (0.451 W/m·K), a 73% reduction compared to the control, confirming SA's dominant role in thermal insulation.
   - CNTs alone increased thermal conductivity at higher dosages (>0.5%) due to their inherent conductive properties, but their combination with SA optimized both insulation and strength.
4. Optimal Mix Design:
   - The M36 mix (0.3% CNT + 6% SA) emerged as the most balanced solution, offering high compressive strength (58 MPa), moderate thermal insulation (0.512 W/m·K), and improved durability (low chloride permeability and porosity).
5. Practical Implications:
   - This study demonstrates that the hybrid use of CNTs and silica aerogel can produce lightweight, high-strength, and energy-efficient concrete, suitable for applications requiring thermal insulation (e.g., building facades) without compromising durability. Future work could explore long-term performance under environmental exposure and cost-effectiveness for large-scale adoption.

The results of the research indicate that concrete has a heat transfer coefficient, compressive strength and durability in specific amounts of silica aerogel and carbon nanotubes. By increasing the amount of silica aerogel alone in the concrete composition, only the characteristic of the heat transfer coefficient decreases and a weakness occurs in the durability and compressive strength of concrete. By increasing the amount of carbon nanotubes up to 0.5%, without using silica aerogel, the amount of permeable pores and the penetration of chloride ions decrease, but the compressive strength and specific electrical resistance improve up to 0.3% of using carbon nanotubes. A combination of two materials, carbon nanotube and silica aerogel, in addition to improving the strength and durability of concrete, reduces the heat transfer coefficient in concrete. So that the best case for mixing is the use of 0.3% carbon nanotube and 4% silica aerogel, it can be seen that the heat transfer coefficient of concrete and the compressive strength of concrete are improved by 73% and 21%, respectively, compared to the control concrete.

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