

Study on Mechanical Properties of Aerogel Concrete at High Temperatures

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Abstract: In this paper, uniaxial compression tests were carried out on aerogel concrete at room temperature and after exposure to high temperatures. The influence of different aerogel contents on the degradation law of mechanical properties of concrete at room temperature and high temperature was investigated. The results show that at room temperature, the strength of concrete first decreases, then increases, and then decreases with the increase of aerogel content. When the aerogel content is controlled at 5%–15%, the strength reduction of the specimens is relatively gentle. After high-temperature treatment, the compressive strength of aerogel concrete exhibits an obvious temperature effect. Before 500 °C, the strength increases slightly and then decreases gradually, indicating that hydration products are still formed and strength develops to a certain extent inside the concrete at this stage. However, the microcracks induced by temperature rise propagate continuously and gradually offset the strengthening effect caused by hydration. After 500 °C, the compressive strength drops sharply, revealing that high temperature significantly aggravates the internal structural damage of concrete. When the temperature rises to 900 °C, the strength loss can reach up to 0.886, and the specimens basically lose their bearing capacity. This reflects that continuous high temperature has caused serious damage to the internal structure of concrete, making it difficult to maintain the original mechanical performance.

Keywords: Aerogel, High temperature, Hydration, Compressive strength.

1. Introduction

Concrete is an indispensable basic material in modern engineering construction. Owing to its excellent workability, mechanical strength, durability, convenient construction, safety and stability, concrete has been widely used in various engineering structures. Although concrete itself is a non-combustible material, complex physical and chemical changes will occur inside it when exposed to fire or long-term high-temperature environments. These changes significantly deteriorate the mechanical properties of concrete, resulting in the degradation of structural strength, directly reducing the bearing capacity and durability of components, and further threatening the safety of the entire building structure.

This indicates that conventional concrete is prone to performance degradation under high temperatures, such as strength reduction, which seriously affects the safety and durability of structures [1-3]. As a new type of nanomaterial with a unique structure, aerogel has ultra-low density, high porosity and excellent thermal insulation properties. Therefore, adding aerogel into concrete can take advantage of the thermal stability and thermal insulation performance of aerogel, which can alleviate the internal structural damage of concrete caused by high temperature to a certain extent, and is expected to improve the thermo-mechanical properties of concrete in high-temperature environments [4-5].

2. Experimental

2.1. Experimental Materials

Ordinary Portland cement P·O 42.5 was used in this experiment. The coarse aggregate (crushed stone with a particle size of 5–10 mm) and manufactured sand were obtained from a sand and gravel quarry in Jiaozuo. The silica aerogel powder used was produced by Lü'ao Thermal Insulation Material Co., Ltd., Langfang, Hebei Province. In accordance with the Specification for Mix Proportion Design

of Ordinary Concrete (JGJ 55—2011), concrete with a designed strength grade of C40 was prepared. The material consumption per cubic meter was as follows: cement 400 kg, water 180 kg, coarse aggregate 1154 kg, and sand 651 kg. The corresponding water-cement ratio was 0.45, and the sand ratio was 36%. Tap water was used for mixing.

2.2. Specimen Preparation

According to literature review and experimental analysis, the compressive strength of concrete decreases significantly when aerogel replaces cement by an equal volume exceeding 30%. Moreover, a higher aerogel replacement ratio makes it more difficult to vibrate and compact the concrete specimens. Therefore, concrete mixtures with different aerogel contents were designed by replacing cement with aerogel at 0%, 5%, 10%, 15%, 20%, and 30% by equal volume. Firstly, cement, aggregate, and aerogel were dry-mixed thoroughly in a mixer. An appropriate amount of water and water reducer was then added, and mixing was continued until the fresh concrete exhibited satisfactory workability. The mixture was cast into cylindrical molds of 50 mm × 100 mm following standard procedures. After being vibrated and compacted, all specimens were cured under standard curing conditions for 28 days.

2.3. Experimental Methods

The fully cured standard concrete specimens incorporated with different aerogel contents were prepared for high-temperature treatment, and all specimens were carefully checked to ensure no initial surface defects before heating. Subsequently, the qualified specimens were placed evenly into a high-temperature muffle furnace for gradient heating treatment, with five target temperature levels set as follows: 25 °C (room temperature, control group), 200 °C, 300 °C, 600 °C, and 900 °C. The heating rate was strictly controlled at a constant 5 °C/min to avoid uneven thermal stress caused by rapid heating. During the entire heating process, a high-

precision TM-902C digital temperature controller was adopted to monitor and record the real-time furnace temperature and relevant data at five-minute intervals, ensuring accurate temperature control and complete data traceability. Once the furnace temperature reached the preset target value, all specimens were kept under isothermal conditions for a continuous 1 hour to ensure uniform thermal penetration and full temperature distribution inside each specimen, and the macroscopic appearance changes such as color and crack development were observed and recorded in real time during this period. After the constant temperature treatment finished, the specimens were taken out and cooled naturally to room temperature in a dry and ventilated environment to avoid rapid cooling damage, and then the uniaxial compressive strength test was carried out immediately following the relevant standard procedures.

2.3.1. Uniaxial Compression Test

Uniaxial compression tests for all aerogel concrete specimens were conducted in strict accordance with the Chinese national standard Standards for Test Methods of Physical and Mechanical Properties of Concrete (GB/T 50081-2019), ensuring the test process meets standard specifications and data reliability. Cylindrical test specimens with a standard dimension of 50 mm × 100 mm (diameter × height) were adopted for all compression tests, and each specimen surface was polished smoothly before testing to eliminate unevenness and ensure uniform stress distribution during loading. All tests were performed using a YNS600 microcomputer-controlled electro-hydraulic servo universal testing machine, which features high precision and stable loading performance. During the formal test, a continuous, uniform and steady load was applied at a fixed stress rate of 0.5 MPa/s until the specimen lost bearing capacity and failed completely. The loading process was stopped immediately after specimen failure, and the peak compressive load and failure data were automatically collected and recorded by the testing machine. For each group of specimens with the same aerogel content and heating temperature, three parallel specimens were tested, and the arithmetic mean of the three valid test results was taken as the final compressive strength value to reduce test errors and ensure data accuracy.

3. Results and Discussion

3.1. Uniaxial Compressive Strength at Room Temperature

The variation trend of the compressive strength of aerogel concrete with different aerogel contents at room temperature is illustrated in Fig. 1. It can be clearly observed from Fig. 1 that the incorporation of aerogel has a notable influence on the compressive strength of concrete. In general, the addition of aerogel leads to a reduction in the compressive strength of concrete, and the degree of strength degradation becomes increasingly significant with the gradual increase in aerogel content.

At the standard curing age of 28 days, the compressive strength of the reference group (without aerogel) reaches 39.67 MPa, which serves as the benchmark for evaluating the strength variation of aerogel-modified concrete. In contrast, the compressive strength of concrete specimens incorporating different contents of aerogel exhibits obvious differences and shows a generally downward trend.

Specifically, compared with the reference group, the compressive strength of aerogel concrete specimens with

aerogel contents of 5%, 10%, 15%, 20%, and 30% decreases by 11.22%, 2.62%, 9.48%, 15.35%, and 39.22%, respectively. It can be found that the reduction amplitude is relatively mild when the aerogel content is low, whereas a sharp decline in compressive strength occurs when the aerogel content is excessively high (e.g., 30%). This indicates that excessive aerogel incorporation will seriously weaken the mechanical properties of concrete, which should be reasonably controlled in practical engineering applications.

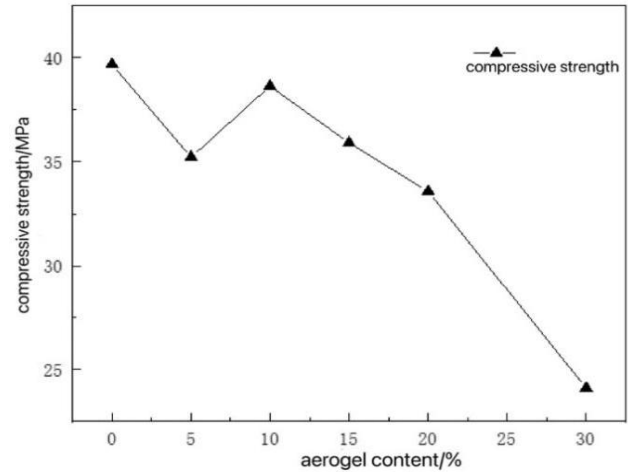


Figure 1. Compressive strength of cylindrical specimens with different dosages at room temperature

According to Fig. 1, the compressive strength of aerogel concrete shows a trend of decrease, followed by increase, and then decrease with the increase of aerogel content. From the experimental data, the compressive strength of aerogel concrete fluctuates slightly within the aerogel content range of 5% to 15%.

When the aerogel content is 5%, the compressive strength of the concrete specimen is measured to be 35.22 MPa. As the aerogel content is increased to 10%, the compressive strength is improved to 38.63 MPa, showing a certain degree of enhancement compared with the specimen containing 5% aerogel. However, when the aerogel content is further raised to 15%, the compressive strength decreases to 35.91 MPa. Although this value is still slightly higher than that of the specimen with 5% aerogel, it is obviously lower than that of the specimen with 10% aerogel.

This phenomenon may suggest that the strengthening effect of aerogel tends to become negligible once its content exceeds 10%. Excessive replacement of cement with aerogel may introduce adverse effects on the internal microstructure, pore structure, interfacial transition zone and overall mechanical performance of the composite material, which in turn leads to the decline in compressive strength.

On the whole, within the aerogel content range from 5% to 15%, the overall influence of aerogel dosage on the compressive strength of the concrete specimens is not particularly significant. Nevertheless, the compressive strength corresponding to 10% aerogel content is relatively higher than those at 5% and 15%, which preliminarily indicates that an **optimal aerogel content** exists within the range of 5% to 15% for achieving relatively better compressive strength performance.

3.2. Apparent Morphology of Concrete After High Temperature

The apparent morphology and surface characteristics of concrete specimens exhibit significant and progressive

changes with increasing heating temperatures, as reflected in variations in color, surface integrity, crack development, and macroscopic damage. The evolution of apparent morphology can directly reflect the internal structural deterioration of concrete subjected to elevated temperatures, thereby providing a visual basis for evaluating its thermal stability and residual mechanical properties.

When the target furnace temperature reaches 300 °C, the overall appearance of the concrete specimen remains relatively intact. The surface is still comparatively flat and smooth, with no obvious through-cracks or macro-cracks observed under visual inspection. Nevertheless, a distinct color change can be identified: the original grayish-cyan color of concrete gradually deepens and transforms into a noticeable reddish-brown hue. Such color variation is mainly attributed to the oxidation of iron-containing components and the initial dehydration of cement hydrates. At this temperature level, the thermal damage to the concrete matrix is relatively slight. The internal microstructure remains generally stable, and the bonding state between the matrix and aggregates is not seriously disrupted. Therefore, the macroscopic structural integrity and basic mechanical performance of concrete are well preserved at 300 °C.

As the heating temperature rises to 500 °C, the deterioration of apparent morphology becomes increasingly evident. Visible microcracks begin to initiate and propagate on the specimen surface, and the surface flatness deteriorates markedly compared with that at 300 °C. This phenomenon demonstrates that the high-temperature environment has significantly aggravated the internal damage and structural degradation of concrete. Under the action of continuous thermal stress and dehydration shrinkage, the internal structure gradually becomes fragile, and the overall integrity is substantially reduced.

The main mechanisms responsible for such deterioration can be summarized as follows. Firstly, a large amount of free water and physically adsorbed water inside the concrete matrix evaporate rapidly at approximately 500 °C, resulting in notable volume shrinkage of the cement paste. Secondly, calcium hydroxide (CH), one of the main cement hydration products, starts to decompose noticeably under this temperature, further destroying the structural stability of the hardened matrix. The combined effects of water loss, thermal shrinkage, and decomposition of hydration products destroy the compact internal structure, reduce the integrity and stiffness of the material system, and eventually lead to the formation and expansion of microcracks on the concrete surface. In addition, previous research has confirmed that the continuous dehydration of calcium silicate hydrate (C-S-H) gel within the temperature range of 250–400 °C also weakens the bonding strength of the matrix and provides favorable conditions for crack initiation and propagation.

When the temperature is further elevated to 700 °C, the thermal damage of concrete develops more severely. The number and length of surface cracks increase significantly, and some individual microcracks tend to connect with each other to form longer and deeper cracks. Meanwhile, the color of the specimen changes from the initial grayish cyan to off-white or light gray. Such obvious color and morphological variations indicate that the internal deterioration of concrete has reached a relatively serious level. The primary reason is that most calcium hydroxide in concrete has decomposed into calcium oxide, accompanied by volume deformation and stress concentration. Moreover, the calcium silicate hydrate

gel, which provides the main strength for concrete, also begins to thermally decompose at this temperature, resulting in a sharp reduction in the cohesion and load-bearing capacity of the matrix.

Upon heating to 900 °C, the concrete undergoes extremely severe structural damage. Both the number and width of surface cracks increase dramatically, and large-scale surface spalling and local peeling can be visually observed. The color of the specimen turns yellowish gray or even pale yellow, which is a typical symbol of serious thermal decomposition and structural collapse. Under such a high temperature, calcium silicate hydrate and calcium hydroxide are almost completely decomposed, and their contribution to strength is basically lost. Meanwhile, calcium carbonate originating from aggregates or carbonation products begins to decompose extensively, generating calcium oxide and releasing a large amount of carbon dioxide. The continuous decomposition reactions and severe volume instability completely destroy the original structure of concrete. As a result, the specimen has suffered catastrophic damage and basically lost its bearing capacity and mechanical properties.

3.3. Compressive Properties of Aerogel Concrete After High Temperature

3.3.1. Compressive Strength

To investigate the influence mechanism and evolution law of high-temperature environments on the compressive performance of concrete, a series of uniaxial compressive strength tests were conducted on concrete specimens subjected to different target heating temperatures. The variation in compressive strength under different thermal conditions is systematically presented in Fig. 2. Through comparative analysis of the test data, the degradation characteristics and internal mechanism of concrete compressive strength under elevated temperatures can be clearly revealed.

When the furnace temperature increases gradually from 25 °C (room temperature) to 150 °C, the compressive strength of all concrete specimens exhibits an overall continuous downward trend. With aerogel contents ranging from 0% to 30%, the compressive strength decreases by 8.9%, 5.26%, 11.73%, 10.83%, 7.24%, and 5.68%, respectively, compared with that at room temperature. The primary reason for such strength reduction is that the relatively low high temperature below 150 °C mainly induces the rapid evaporation of free water and physically adsorbed water inside the concrete matrix. The loss of internal moisture increases the number and volume of internal pores, weakens the integrity of the cementitious structure, and reduces the compactness of the material. Consequently, the internal stress transfer path is partially interrupted, and the overall compressive strength of concrete is correspondingly decreased.

When the heating temperature is further controlled within the range of 150 °C to 300 °C, it can be clearly observed from the variation curve depicted in Fig. 2 that the compressive strength of concrete no longer decreases continuously. Instead, it shows a noticeable upward trend and reaches the peak value of 39.50 MPa at 300 °C. This special temperature-strength relationship is mainly attributed to two key strengthening mechanisms.

Firstly, within this temperature interval, the thermal activation effect promotes the secondary hydration of unhydrated cement particles inside the concrete. More calcium silicate hydrate and other hydration products are

generated, which fill the internal pores and improve the mechanical properties of the matrix. Secondly, the appropriate dehydration of calcium silicate hydrate gel during heating contributes to the formation of a more compact and stable network structure in the cementitious matrix. Moderate shrinkage of the matrix effectively reduces the internal porosity and initial defects, thereby enhancing the uniformity and compactness of the internal structure. Meanwhile, the chemical bonding and interfacial adhesion between the cement matrix and aggregate are also improved, which strengthens the overall integrity of the specimen.

Under the combined influence of the above positive effects, the compressive strength of concrete increases steadily with rising temperature in the range of 150 °C to 300 °C and achieves the maximum value at 300 °C.

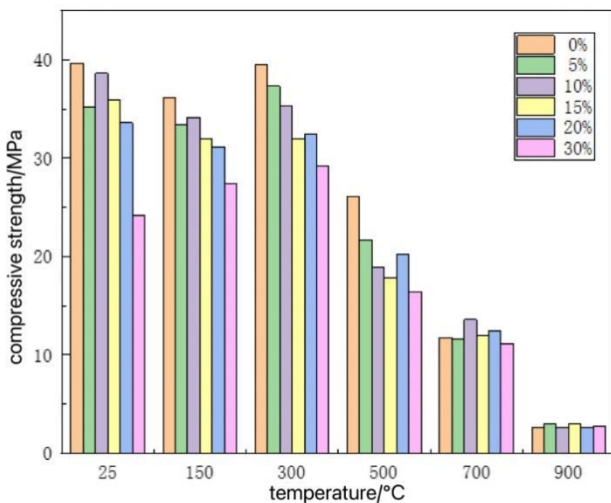


Figure 2. Compressive strength of cylindrical specimens at different temperatures

When the heating temperature reaches 500 °C, the compressive strength of aerogel concrete specimens decreases significantly compared with that at 300 °C. Severe thermal damage occurs inside the material, accompanied by obvious deterioration of macroscopic mechanical properties. Among all the mixing proportions, specimens with 10% aerogel content exhibit relatively better compressive performance than other groups, demonstrating more excellent high-temperature resistance and structural stability. This indicates that a proper amount of aerogel can alleviate the thermal damage of concrete to a certain extent and help maintain its mechanical properties under elevated temperature conditions.

As the temperature continues to rise to 700 °C, the thermal deterioration of concrete becomes increasingly serious. The number, length and width of surface cracks increase significantly, and some microcracks gradually connect and penetrate to form macroscopic cracks. Correspondingly, the compressive strength of all concrete specimens decreases more obviously. Under the action of such a high temperature, the hydration products inside the concrete undergo severe decomposition, and the bonding performance between the matrix and aggregates is greatly weakened, resulting in a sharp reduction in load-bearing capacity.

When exposed to a high temperature of 900 °C, the concrete suffers extremely severe structural damage. A large number of internal cracks initiate, propagate and interconnect rapidly, resulting in the overall deterioration of the material structure and a sharp decline in compressive strength. Taking aerogel concrete with 10% aerogel content as a typical

example, its compressive strength drops dramatically from 38.63 MPa at room temperature to only 2.74 MPa, with a strength loss rate as high as 92.9%. Even under such extreme high-temperature conditions, this group of specimens still performs the best among all samples, with higher residual compressive strength than the reference group and other mixing proportions. This fully reflects the positive effect of aerogel on improving the high-temperature resistance of concrete.

The overall experimental results show that under the action of high temperature, the internal structure of concrete will be seriously damaged, and the compressive performance will be greatly degraded. With the increase of temperature, the decomposition of hydration products, the generation and development of microcracks, the deterioration of interfacial transition zone and the loss of material integrity work together, leading to the continuous reduction of compressive strength. However, the incorporation of aerogel can effectively alleviate this degradation trend to a certain extent. The overall compressive performance of aerogel concrete is more prominent than that of the reference group without aerogel in most temperature ranges, and it can still retain relatively better bearing capacity and structural integrity even under extreme high-temperature conditions.

The main reason lies in the unique porous structure and excellent thermal insulation property of aerogel. The low thermal conductivity of aerogel can slow down the heat transfer rate inside the concrete, reduce the temperature difference and thermal stress inside the specimen, and thus inhibit the initiation and propagation of microcracks. In addition, the appropriate addition of aerogel can optimize the internal pore structure and improve the deformation adaptability of concrete under high temperature, so as to reduce the thermal damage degree.

Therefore, it can be concluded that the excellent thermal insulation property of aerogel can effectively improve the mechanical properties and structural stability of concrete at high temperature, significantly enhance its high-temperature compressive resistance, and provide a feasible way for the development and application of concrete materials in high-temperature or special thermal environments.

4. Conclusion

At room temperature, the aerogel content has a significant effect on the compressive strength of concrete. The strength shows a trend of first decreasing, then increasing, and then decreasing with the increase of content. The strength reduction is small within the range of 5%–15% content, among which 10% content is the optimal content with the best compressive performance.

Under high temperature, the compressive strength of aerogel concrete presents obvious temperature segmentation characteristics: the strength decreases within 150 °C, rises slightly between 150 °C and 300 °C and reaches the peak at 300 °C, decreases sharply after 500 °C, and basically loses bearing capacity at 900 °C.

With the increase of temperature, the appearance of concrete gradually develops from deepening color to surface cracking and spalling, and the internal hydration products decompose continuously. 500 °C is the key temperature point for the significant aggravation of structural damage, and the high-temperature deterioration effect is obvious.

Relying on its excellent thermal insulation performance, aerogel can effectively improve the high-temperature

compressive performance of concrete. Specimens with 10% aerogel content are superior to the reference group and other content groups at all temperature stages, with better high-temperature resistance and damage resistance.

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