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Research Article

Experimental Research on Dehydration Process and Strength of Concrete Influenced by Drying Temperature and Concrete Size

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Moisture has a significant effect on the properties of concrete, and drying concrete in an oven is a common method to obtain specimens with different moisture content. In this paper, C30 concrete specimens with different sizes were oven-dried at constant temperatures of 60, 80, 105, 120, and 150 °C, respectively. The change of specimen mass, ultrasonic testing, and compressive and splitting tensile strength were tested before and after drying. The size effect and the size effect law (SEL) of concrete were analysed. The results indicated that the maximum drying rate and water loss ratio of the specimens with different sizes under the same drying temperature are basically the same. The larger the size, the longer the drying time. After drying, the concrete compressive and splitting tensile strength have increased to varying degrees, and the smaller the size, the greater the increase. For C30 concrete with different sizes, the drying temperature that has the minimal influence is 105 °C. The SEL was modified by introducing drying temperature, and the formulas were obtained after drying.

1. Introduction

The moisture content of concrete has an obvious effect on the mechanical properties [1–3]. For studying moisture effect, researchers must get the concrete specimens with zero moisture content by isothermal drying firstly [4–6]. Oven-drying is the most widely used method in test; however, there is no standard for controlling the specimen size and the recommended drying temperature. In different drying conditions, researchers get the dry-based concrete with different sizes, ignoring the influence of specimen size on drying results. The current research on concrete with different sizes is mainly focused on the mechanical properties [7–9], but isothermal drying law and the change of size effect after drying have rarely been studied. Liu et al. [10] dried three sizes concrete specimens ($100 \times 100 \times 100\,\text{mm}^3$, $100 \times 100 \times 300\,\text{mm}^3$, and $150 \times 150 \times 150\,\text{mm}^3$) at the same drying temperature. Yurtdas et al. [11] studied the effect of drying on concrete mechanical properties, and the specimen sizes were $40 \times 40 \times 160\,\text{mm}^3$ and $\varnothing 160 \times 320\,\text{mm}^3$. Rucker-Gramm et al. [12] placed $240 \times 45 \times 45\,\text{mm}^3$ concrete specimens in an oven. Han et al. [13] studied the effect of isothermal drying on the strength of concrete without considering the size effect. In above tests, the strength of concrete after drying was affected by the size, but the size effect to drying temperatures was not considered. The concrete specimens with different sizes have different internal temperature distribution at the same external constant drying temperature. In addition, the random distribution of coarse and fine aggregates, cement mortar, and the content and distribution of initial defect are different, which will also cause the difference in drying results, such as drying time, water loss ratio, and strength change.

After drying, the concrete strength change is the result of the competition between the microcracks caused by water evaporation and the increased solid-phase density caused by further hydration during drying process [14–16]. The drying temperature that has the minimal influence of the C30 concrete specimen with a side length of 100 mm is 105°C. The effect of the specimen size was not taken into account

Table 1: Mix proportions and the major parameters of C30 concrete.

Cement (kg)	Fly ash (kg)	Water (kg)	Sand (kg)	Small stone (5–20 mm)/kg	Compressive strength at 28 d (MPa)
360	40	180	673	1147	37.4

when analysing the strength change. Because of the size effect of concrete, the difference in specimen size makes the drying rates and the time different, which cause different damage in concrete, and will inevitably cause changes of the size effect after drying. In order to monitor the change of concrete during drying, ultrasonic testing is the most commonly used method in nondestructive testing of concrete [17]. The change of moisture in concrete will also cause the change of ultrasonic wave velocity, which also provides the possibility of ultrasonic detection of moisture change and structural change caused by drying [18].

In this paper, the cube concrete specimens were prepared, and the sizes were $70.7 \times 70.7 \times 70.7\,\text{mm}^3$, $100 \times 100 \times 100\,\text{mm}^3$, and $150 \times 150 \times 150\,\text{mm}^3$, respectively. The drying temperatures were 60, 80, 105, 120, and 150°C, respectively. The change of specimen mass, ultrasonic testing, and compressive and splitting tensile strength were tested before and after drying. The drying laws and the change of size effect were analysed, and the formula of the size effect law (SEL) was established after drying at different temperatures. Finally, the drying temperature with the least influence on the concrete size effect and strength was determined.

2. Materials and Methods

In this paper, the raw materials for the concrete include ordinary Portland cement (P.O.42.5), fine aggregate, coarse aggregate, fly ash, and the water. For cement, the water consumption for a normal consistency is 28.78%, and the initial and final setting times are 3.7 h and 5.7 h, respectively. At 28 days, the compressive and splitting tensile strength are 49.3 and 8.43 MPa, respectively. For fine aggregate, the fineness modulus, dense packing density, and apparent density are 2.75, $1771.67\,\text{kg/m}^3$, and $2560\,\text{kg/m}^3$, respectively. For coarse aggregate, the particle size, bulk density, and apparent density are 5–20 mm, $1648.71\,\text{kg/m}^3$, and $2620\,\text{kg/m}^3$, respectively. For fly ash, the density, bolster specific surface area, and water content are $2340\,\text{kg/m}^3$, $360\,\text{m}^2/\text{kg}$, and 0.5%, respectively. The water is the ordinary water in lab.

The drying equipment was an electrothermostatic blast oven, with the working chamber size of $800\,\text{mm} \times 800\,\text{mm} \times 1000\,\text{mm}$, and it can heat up to 300°C. The accuracy of the electronic balance is 1.0 g. The microcomputer-controlled universal testing machine with a capacity of 1000 KN was used for compressive and splitting tensile test. The nonmetallic ultrasonic analyzer was used for comparing the change of concrete internal structure before and after drying. The ultrasonic sampling period and the frequency of the analyzer were $0.02\,\mu\text{s}$ and 50 KHz, respectively. Concrete specimens were cube shaped with a side length of 70.7 mm, 100 mm, and 150 mm, respectively. The mix proportion of concrete was shown in Table 1.

After 28 days of standard curing, where the curing temperature is 20 ± 5°C and the relative humidity (RH) is above 95%, the specimens were divided into 6 groups with one assigned to the standard control groups and the other five to the test groups. Each group was divided into three parts which contained six specimens for each size of $70.7 \times 70.7 \times 70.7\,\text{mm}^3$, $100 \times 100 \times 100\,\text{mm}^3$, and $150 \times 150 \times 150\,\text{mm}^3$, respectively. The six specimens were divided into two groups for compressive and splitting tensile test. In the standard control groups, the strength of the specimens was tested directly, and the size effect was analysed. In the test groups, the specimens were weighed, and their ultrasonic velocities were measured twice in the same point before and after drying.

The test specimens were placed in the drying oven at 60, 80, 105, 120, and 150 °C, respectively. The oven was preheated to the specified temperature. The water loss was recorded every one hour during the early drying stage because of the rapid mass loss and then every four hours during the later drying stages until the specimens reached the completely dry state; in this process, the temperature in drying oven should be maintained carefully by weighing the specimens as quickly as possible every time. After the second ultrasonic testing, the specimens were tested for the concrete compressive and splitting tensile test, and the size effect and the SEL were analysed.

3. Results and Discussion

3.1. Analysis of the Law of Dehydration. After drying, the required drying time, total water mass loss, water mass loss ratio, and maximum drying rate for C30 concrete specimen with different sizes at different drying temperatures are summarized in Table 2. Among them, the change trend of the drying rate of concrete specimens at different drying temperatures is basically the same. Taking the drying temperature of 105 °C as an example, the drying rate curve of the concrete specimens of different sizes is shown in Figure 1. The values are the average values of the six specimens, and the water loss ratio is defined as the ratio of lost water mass to the wet concrete specimen mass. The drying rate is the vaporized moisture mass on the unit surface of C30 concrete specimens per unit time and is expressed as kg/(h·m^2).

Figure 1 illustrates that a higher temperature can lead to a decrease in the drying time and increase in water mass loss ratio and the maximum drying rate. A larger concrete size can lead to an increase in the drying time at the same temperature. However, the water mass loss ratio and the maximum drying rate of concrete with different sizes are roughly coincident at the same temperature; it is not affected by the size.

During the drying process, the temperature and vapor pressure in concrete are changed constantly. The vapor

Table 2: Drying results of different sizes of concrete specimens.

Drying temperature/°C	Cube size (mm)	Drying time (h)	Total water loss (g)	Water loss ratio (%)	Maximum drying rate/(kg/(h·m^2))
60	70.7	228	31.00	3.63	0.0556
	100	397	90.67	3.75	0.0722
	150	745	308.77	3.82	0.0642
80	70.7	120	35.33	4.15	0.0901
	100	228	108.67	4.28	0.0944
	150	433	359.33	4.36	0.1062
105	70.7	60	37.67	4.37	0.1223
	100	84	110.33	4.53	0.1306
	150	145	384.50	4.75	0.1272
120	70.7	48	42.67	5.04	0.2001
	100	79	131.67	5.45	0.2111
	150	120	438.67	5.36	0.2049
150	70.7	37	46.33	5.51	0.3445
	100	48	141.00	5.87	0.3944
	150	79	460.67	5.65	0.3944

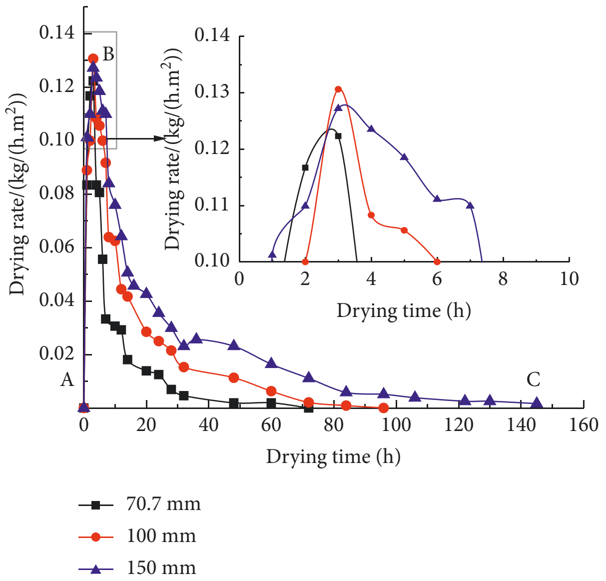

Figure 1: Drying curves of C30 concrete of different sizes at 105 °C.

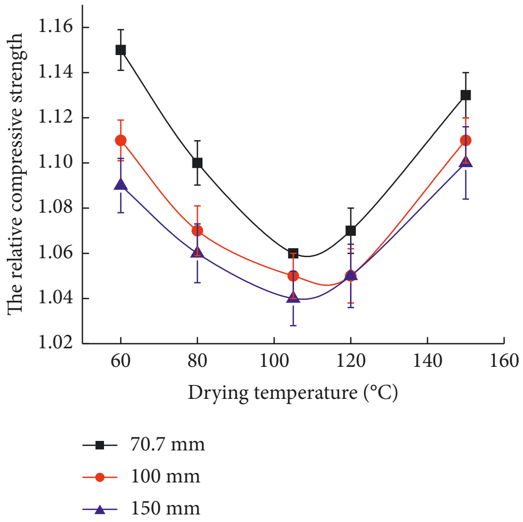

Figure 2: The relative compressive strength.

pressure difference between the inside and outside of the specimen is the driving force for moisture migration [11]. Water evaporation is gradually developed from the outside to the inside, accompanied by changes in temperature stress and vapor pressure difference, which causes the change in the drying rate. According to the change of the drying rate, the drying process can be divided into two stages that were ascent stage (section AB) and descent stage (section BC), as shown in Figure 1. At the beginning of drying, with the temperature on specimen surface rising, the water vaporization on the surface leads to vapor pressure firstly. The temperature difference between specimen inside and surface increases, the vapor pressure gradient becomes larger, and the migration distance of water vapor is short, so the rate of water loss gradually increases, and the drying rate reaches the maximum at point B. However, for the specimens of different sizes, the maximum drying rate is essentially the same, because the moisture content and thermal conductivity are the same, and the drying rate is defined as the ratio of water evaporation per unit surface area. Different from ceramic drying process, there is no constant drying stage. After ascent stage, the drying process becomes the descent stage directly. In the period, with the drying surface going into the inside of the specimen, the distance of water evaporation and the resistance have increased, so the drying rate decreases. At the same temperature, a larger concrete specimen size can lead to an increase in the drying time; this is because a larger size of specimen can lead to longer drying path, greater resistance, and larger vapor pressure difference required for the water evaporation.

3.2. Analysis of the Change of Strength. In this paper, the relative strength was used to indicate the strength change, and it was defined as the ratio of concrete strength in test groups to that in standard control groups. The strength

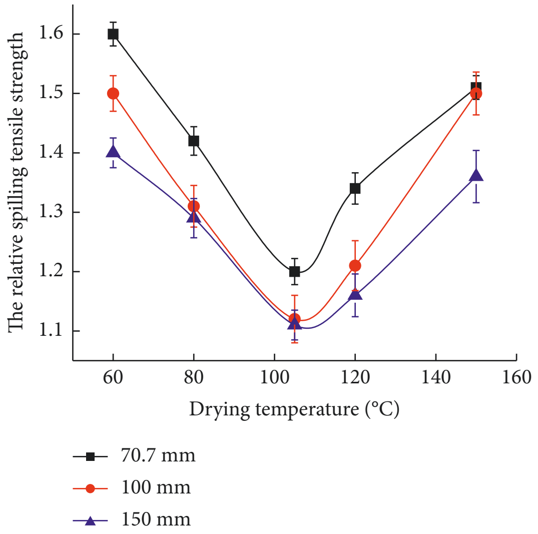

Figure 3: The relative splitting tensile strength.

change was also affected by the curing age, and the concrete strength is converted into the strength at the same age of 28 days [19]. The relative compressive and relative splitting tensile strength of C30 concrete with different sizes after drying at different temperatures are shown in Figures 2 and 3.

As shown in Figures 2 and 3, after drying, the changes of the compressive and splitting tensile strength of C30 concrete with different sizes are basically consistent, and the relative strength initially decreases and subsequently increases with the increase of the drying temperature. Meanwhile, the changes in the splitting tensile strength are much higher. Research shows [20] that, for concrete, the splitting tensile strength is more sensitive to the change of porosity than the compressive strength. The change range of splitting tensile strength is higher than that of compressive strength. Therefore, under the same drying temperature, the changes of splitting tensile strength are much higher.

The strength change trend of concrete with different sizes is basically consistent, and the compressive and splitting tensile strengths of the concrete are always increased. The relative strength initially decreases and subsequently increases with increasing drying temperature, which is basically consistent with the results [13]. Regardless of the change in specimen size, the temperature corresponding to the minimal strength change is substantially the same. It can be considered that the drying temperature that has the minimal influence on the strength is 105°C for C30 concrete; it is not affected by the specimen size. Moreover, it can be observed from Figures 2 and 3 that, at the same temperature, the magnitude of the strength increase of concrete with different sizes is different. The strength of the small-sized specimen is increased by a larger amount than that of the large-sized specimen, which can be explained in the following.

During the drying process, there are two aspects of main changes in the interior of the concrete [21]. On the one hand, dehydration inevitably causes damage in the concrete specimens. This damage mainly originates from physical and chemical changes, which inevitably leads to the porosity change of the concrete [22]. In Zhang's study [23], after drying at 105°C, the volume fraction and the amount of porosity are both increased by 20% and 42%, respectively, as compared to standard groups. The increase in porosity is due to the shrinkage of the paste around the pores occupied by water during the evaporation of water, which enlarges the existing pore radius. The water evaporation creates new "channels" along the weak gap surface, which generates larger pores [24]. The increase of the pores indicates increase of damage inside the concrete.

Due to the different sizes, the increase of porosity of concrete with different sizes is different after drying. In this paper, the difference of porosity can be reflected by the change of ultrasonic wave velocity before and after drying. The ultrasonic results for concrete with different sizes before and after drying under different drying temperatures are shown in Table 3, where column "B" represents test results before drying, column "A" represents test results after drying, and column "C" represents the difference between columns "B" and "A"; the ultrasonic wave velocity values are the average values of the six specimens.

As shown in Table 3, for the same size specimen, a higher drying temperature leads to a larger reduction of ultrasonic wave velocity, which indicates that the porosity increase is larger. At the same drying temperature, a larger specimen size leads to a larger reduction of the ultrasonic wave velocity. With the increase of the size, the vapor diffusion path becomes longer and the resistance increases, and only by absorbing more heat and generating a larger vapor pressure, water vapor can diffuse from the interior of the concrete, which causes the more microcracks damage and leads to a larger reduction in ultrasonic wave velocity [25].

On the other hand, after drying, C-S-H shrinks because of the water loss in the gel pores and C-S-H particles bond more closely after drying because of the increase in surface energy of the cement-based materials [26, 27], which lead to the increase in the solid phase density of the concrete. As we know, after the same curing time, the internal moisture content of concrete specimens with different sizes is basically the same. In this test, the water mass loss ratio of concrete specimens with different sizes is basically the same at the same temperature. Therefore, it can be considered that further hydration degree of concrete with different sizes at the same drying temperature is considered as the same [28]. The competition between the above two aspects leads to changes in the strength of the concrete [11], but the size of concrete has different influence on the two aspects, which eventually leads to different strength growth of concrete with different sizes; the increase in strength of large-sized specimens is smaller than that of small-sized specimens.

3.3. Analysis of the Size Effect.

Size effect means that as the structural size increases, the mechanical properties represented by the strength are no longer constant; this characteristic is referred to as the size effect of concrete [28]. The strength increase of concrete with different sizes caused by

Table 3: The wave velocity of concrete with different sizes at different drying temperatures.

Drying temperature (°C)	The wave velocity (km/h)								
	70.7 mm			100 mm			150 mm		
	B	A	C	B	A	C	B	A	C
60	4.887	4.546	0.341	4.767	4.415	0.352	4.720	4.359	0.361
80		4.428	0.459		4.241	0.526		4.190	0.530
105		4.396	0.491		4.227	0.540		4.166	0.554
120		4.347	0.540		4.210	0.557		4.159	0.561
150		4.219	0.668		4.099	0.668		4.013	0.707

Table 4: Conversion coefficients of strength with different temperatures and sizes.

Drying temperature (°C)	Conversion coefficient of compressive strength			Conversion coefficient of splitting tensile strength		
	70.7 mm	100 mm	150 mm	70.7 mm	100 mm	150 mm
Before drying (20)	0.947	0.966	1	0.848	0.912	1
60	0.898	0.949	1	0.742	0.851	1
80	0.913	0.957	1	0.770	0.898	1
105	0.929	0.958	1	0.784	0.904	1
120	0.929	0.956	1	0.734	0.874	1
150	0.922	0.957	1	0.764	0.827	1

the drying inevitably changes the size effect and SEL of concrete, and this change will affect the selection of the drying temperature that has the minimal influence of concrete with different sizes.

Usually, the standard test specimen for concrete compression and splitting tensile strength is a cube with a size of 150 mm. The conversion coefficient is defined as the ratio of the strength of the standard size test specimen to the nonstandard size test specimen. The conversion coefficients of the compression and splitting tensile strengths of the cube specimen with a side length of 100 mm are 0.95 and 0.85, respectively. The conversion coefficients of concrete samples with different sizes at different drying temperatures are shown in Table 4.

As shown in Table 4, before drying, as the size of specimen decreases, the conversion coefficients of compressive and splitting tensile strength decrease, which indicates that the concrete strength has size effect obviously. The conversion coefficients of the compressive strength of the cube specimen with a side length of 70.7 mm and 100 mm are 0.947 and 0.966, respectively, while the conversion coefficients of the splitting tensile strength are 0.848 and 0.912, respectively.

After drying, concrete strength also has size effect. For the same size specimen, the strength conversion coefficient after drying is smaller than that before drying, which indicates that after drying the size effect has obvious changes. The conversion coefficient change is the smallest at 105 °C, indicating that this temperature has the minimal influence on C30 concrete.

Du [29] believed that the boundary layer effect caused by the nonuniformity of materials and defects is one of the factors affecting the size effect of concrete. During the pouring concrete specimens, the aggregate distribution content at the edge of the specimen is less than that in the inner region, which causes change of the mechanical properties in the concrete surface layer. For small-sized specimen, the proportion of the boundary layer area is relatively large, while that is relatively small for the large-sized specimen, resulting in the difference in performance. After the drying, the temperature stress will cause different contents of microcracks and pores in the two regions due to the different aggregate restraint effects. Lin [30] concluded that the changes in concrete strength were affected by the restraint of the coarse aggregate after drying, which is consistent with the result of this paper. Therefore, the difference between the two regions is enlarged after drying, and the strength of the small-sized specimen with relatively low aggregate content has a greater increase, showing a more significant size effect.

The time dependence caused by the diffusion process is also one of the important factors affecting the size effect of concrete [29]. The isothermal drying process is a process of heat and moisture transfer. In this process, the material properties are changed by the temperature stress and the humidity gradient. After drying, even if the test specimens are at room temperature, the specimen still had residual stress. In order to determine the difference of influence time of temperature stress on concrete with different sizes, the heat transfer process of concrete with different sizes was numerically simulated. In order to simplify model, the concrete is considered to be a homogeneous material. It is defined that when the temperature difference between the center and the surface of the specimen is less than 1.0°C, the specimen has reached the temperature equilibrium state. After calculation, the time for the cube specimens with side lengths of 150 mm, 100 mm, and 70.7 mm to reach equilibrium states was 67 min, 30 min, and 15 min, respectively.

The time taken for the specimens with different sizes to reach an equilibrium state is proportional to the square of their structural size. The time for small-sized specimen to reach the equilibrium state is significantly smaller than that

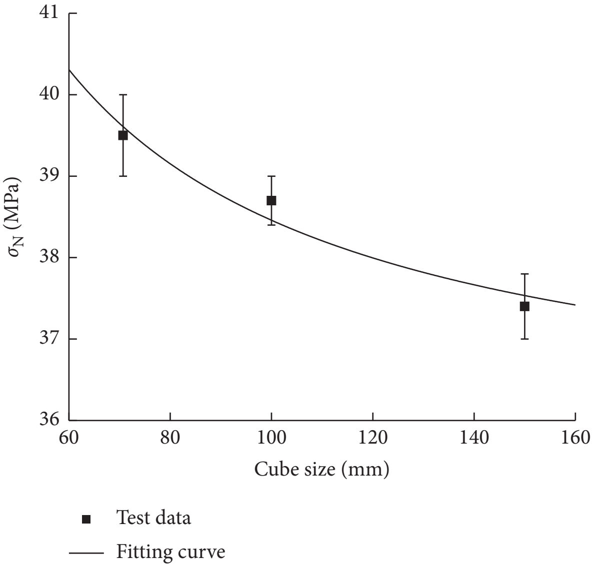

Figure 4: The fitting curve of concrete SEL before drying.

of the large-sized specimen. Hence, the small-sized specimen is less affected by temperature stress and has less storage energy and residual stress, resulting in less increase of pores and damage. Therefore, the small-sized specimen shows a larger strength increase in the competitive mechanism, and the size effect is more obvious.

3.4. The Size Effect Law. Bažant [31] established the theory of fracture-SEL based on energy release theory. It is believed that the release of energy in the fracture process zone during the loading process leads to the size effect, and the relationship between the nominal compressive strength σ_{N} of the specimen of any size and the cube side length D of the specimen was obtained as follows:

$$\sigma_N = \sigma_\infty\left(1 + \frac{D_b}{D}\right), \tag{1}$$

where σ_∞ represents nominal compressive strength of the specimen with a very large side length and D_b represents effective thickness of the cracked boundary layer, which is determined by experiment.

According to the test data, the fitting curve and the SEL of compressive strength of C30 concrete before drying were obtained, and R^2 was 0.922, as shown in equation (2) and Figure 4.

$$\sigma_{N,30} = 35.69 \times \left(1 + \frac{7.77}{D}\right). \tag{2}$$

As shown in equation (2), R^2 was 0.922, indicating that the calculation results are consistent with the experimental data, and the SEL can be used to predict the strength of the concrete with different sizes. After drying at different temperatures, the compressive strength of concrete is tested at room temperature. It is found that the SEL is still adapted for the strength prediction. After drying at different temperatures, the concrete strength shows different SEL. The temperature coefficients α_1 and α_2 were introduced for the SEL of C30 concrete, and the modified SEL was obtained as shown in the following equation:

$$\sigma_{N,30} = 35.69\alpha_1 \times \left(1 + \frac{7.77\alpha_2}{D}\right). \tag{3}$$

Table 5: Temperature parameters at different drying temperatures and R^2.

Temperature (°C)	60	80	105	120	150
α_1	1.027	1.026	1.020	1.027	1.068
α_2	2.184	1.763	1.389	1.394	1.571
R^2	0.998	0.875	0.948	0.999	0.985

Temperature parameters and R^2 of the modified SEL were obtained, as shown in Table 5.

As shown in Table 5, after drying at different temperatures, the change of σ_∞ (nominal compressive strength of the specimen with a very large side length) in equation (1) is basically the same, and the temperature coefficient α_1 is close to 1.0, which indicates that the drying temperature has little effect on σ_∞, while the effect of drying temperature on the SEL is mainly on the cracked boundary layer effective thickness D_b. Bažant [32] considered that, in geometrically similar concrete specimens, D_b is related to the crack propagation zone size c_f; it is only related to the nature of the material itself. During the isothermal drying process, the effect of temperature changes the microstructure of the material and produces the residual stress, which increases the porosity of concrete and changes the SEL of concrete after drying at different temperatures. Comparing the temperature coefficients α_2 at different temperatures, it can be seen that α_2 is the smallest when the drying temperature is 105°C, which indicates that the changes of SEL at this temperature are the smallest, and this temperature has the minimal influence on C30 concrete. It can be seen from R^2 that the test data are in good agreement with the formula of SEL, indicating that the drying temperature coefficients are reasonable, which can supply a basis for predicting the compressive strength of C30 concrete of any sizes after drying at different temperatures.

Analysis of how drying temperature affects a much larger size concrete specimen and the range of drying temperatures and the size of concrete used in the test will be refined in future studies. Above size effect analysis is mainly compressive strength, and the splitting tensile strength of concrete will also be studied in future research.

4. Conclusions

In this paper, concrete specimens of C30 with three sizes were oven-dried at different temperatures ranging from 60 to 150 °C. The change of specimen mass, ultrasonic testing, and compressive and splitting tensile strength were tested before and after drying. And the size effect law of concrete was also determined by considering the drying temperature. The following conclusions were reached:

(1) When the concrete reaches the completely dry state, the water loss ratio and the maximum drying rate of concrete with different sizes are roughly the same, and the drying time increases with the increase of the size.

(2) After drying, the changes of the compressive and splitting tensile strength of C30 concrete with different sizes are highly similar; that is, the relative strength initially decreases and subsequently increases with the increase of the drying temperature. Meanwhile, the changes in the splitting tensile strength are much higher.

(3) After drying, the magnitude of the increase in strength of concrete with different sizes is different. The smaller the size, the greater the strength increase, and it shows the obvious size effect of concrete strength. After drying, the concrete strength still meets the requirement of size effect law. The modified size effect law of concrete was obtained by introducing the temperature coefficients.

(4) 105°C is still the drying temperature that has the minimal influence on the strength and size effect of C30 concrete.

Data Availability

All data used during the study appear is correct.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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