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ARTICLE

Effect of water-to-cement ratio on internal relative humidity and autogenous shrinkage of early-age concrete internally cured by superabsorbent polymers

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Abstract
Self-desiccation is one common phenomenon of concrete with low water-to-cement (w/c) ratios, which may lead to the decrease of internal relative humidity (IRH), and therefore causing autogenous shrinkage (AS). Superabsorbent polymers (SAPs) are used as a kind of internal curing material to mitigate AS of concrete. The IRH and AS are significantly affected by the w/c ratio, and several attempts have been made to investigate the IRH or AS of concrete with different w/c ratios. However, the prediction model of AS considering IRH and w/c ratio of internally cured (IC) concrete is limited. In the present study, the effect of w/c ratio on IRH and AS of IC concrete was investigated, and a two-stage prediction model of AS based on the results of IRH for IC concrete considering the effect of w/c ratio was proposed. The experiment results and analysis indicated that IRH of IC concrete increased as increase of w/c ratio, and development of IRH experienced two stages: a water-vapor saturated stage with 100% RH (stage I), and a gradually reducing stage in which IRH decreased gradually (stage II); critical time of IC concrete increased as increase of w/c ratio; expansion peak of IC concrete increased as increase of w/c ratio; AS and AS rate of IC concrete decreased as increase of w/c ratio; IRH, critical time, and expansion peak of IC concrete were higher than that of ordinary concrete; AS and AS rate of IC concrete were lower than that of ordinary concrete.

KEYWORDS
autogenous shrinkage, concrete, early age, internal curing, internal relative humidity, prediction model, superabsorbent polymers, water-to-cement ratio

1 | INTRODUCTION

Concrete has been widely used in modern buildings and infrastructures for many advantages, and concrete with high strength develops with the decrease of water-to-cement (w/c) ratio.[1–3] Self-desiccation is one common

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phenomenon of concrete with low w/c ratios,[4,5] which may lead to the decrease of internal relative humidity (IRH), and therefore causing autogenous shrinkage (AS).[6] Generally, the shrinkage is inversely proportional to the IRH of concrete, and higher IRH causes lower shrinkage in concrete.[7] The products of hydration will fill the room between the solid particles, form menisci, and increase the capillary tension force in the concrete.[8,9] The AS is caused when the distance between the solid particles is reduced due to the capillary tension force.[8] The ratio of AS to total shrinkage of concrete increases evidently with decreasing w/c ratio.[10] When the w/c ratio is lower than 0.50, AS significantly decreases cracking resistance if the concrete structure is under restrained condition.[11] Tensile stress will occur in concrete during the process of shrinkage when concrete is restrained by adjunct materials, connecting members, and shrinkage gradient. Early age is an important period in the life cycle of concrete because the tensile strength of concrete at early age is weak.[12] Cracks tend to occur in early-age concrete when tensile stress overcomes its tensile strength, and moisture as well as aggressive substances can penetrate into the interior of concrete through cracks at early age.[13,14] Several problems of strength and durability may be constituted by cracks.[15,16] Considering that w/c ratio has significant effects on IRH and AS at early age,[4] the investigations on the IRH and AS of concrete with different w/c ratios at early age are necessary.

Different curing methods are utilized to prevent the reduction of IRH during the cement hydration to mitigate the development of AS and decrease the risk of cracking.[17–19] The traditional external curing method only penetrates on the surface layer of the concrete. Besides, the cracking problems of concrete with low w/c ratio cannot be mitigated effectively by water curing due to its compact pore structure and low permeability.[19] On the contrary, internal curing is a method of mixing water-absorbing materials into concrete after water absorption, which makes up for the deficiency of traditional external curing method.[20] The IRH decreases due to self-desiccation when the concrete is under sealed condition.[21] When the humidity gradient occurs between the cementitious material matrix and internal curing materials, such as lightweight aggregates, pumice, expanded clay, and superabsorbent polymers (SAPs), the moisture loss due to the hydration of concrete will be compensated by the water released by the internal curing materials,[21] which can maintain the IRH during self-desiccation and mitigate the AS in concrete. SAPs are cross-linked polyelectrolyte polymers with high capacity of water absorption,[22] and the incorporation of SAPs is proved to be effective in reducing AS.[23] SAPs absorb water and swell during the process of water mixing, and then the SAPs serve as a curing agent in concrete through desorbing the water. Moisture content in pores within concrete increases due to the additional water released by the SAPs, which can delay the reduction of IRH, mitigate AS, increase durability, and improve cracking resistance.[10,24] A considerable amount of research has been published on the AS or IRH of concrete internally cured (IC) by SAPs. Snoeck et al.[8] study the AS of IC concrete with the w/c ratio of 0.30 and 0.35. Kong et al.[25] investigate the AS of IC concrete, and reveal that the development of AS under drying condition as well as the drop of IRH in sealed high strength concrete specimens is postponed by the incorporation of SAPs. The effect of SAPs on reducing AS has also been found by Jensen et al.[26] and Craeye et al.[27] Wang et al.[28] reveal that the increase of SAP dosage delays the IRH decline and reduces the AS, but compromises the mechanical properties of concrete. Shen et al.[29] investigate the IRH and AS of IC concrete, and results reveal that the incorporation of SAPs increases the IRH and decreases the AS of concrete at early age. The water consumption caused by self-desiccation in concrete under sealed condition is partially complemented by the internal curing water released by SAPs. IRH and AS are affected by w/c ratio of concrete, and several attempts have been made to investigate the effect of w/c ratio on IRH or AS.[4,30,31] For instance, Zhang et al.[32] investigate the AS of concrete with w/c ratio ranging from 0.26 to 0.35, and results reveal that the AS decreases as increase of w/c ratio. Jiang et al.[33] investigate the IRH of concrete with different w/c ratios, and results reveal that reduction of IRH decreases as increase of w/c ratio. However, few studies have investigated the effect of w/c ratio on IRH and AS of IC concrete. Therefore, the investigations on the IRH and AS of in IC concrete considering the effect of w/c ratio are necessary.

Considering that the existing methods for determining the AS of concrete is complicated, if the prediction model of early-age AS based on the results of IRH is proposed, the AS can be easily estimated by the results of IRH because the determination of IRH is easier than that of AS. The existing prediction models of the correlation between AS and IRH are mainly divided into two categories: one is theoretical model based on the microstructure of concrete, and explains the relevant phenomena from the mechanism[30,31]; the other one is empirical model based on the test results and engineering data.[4] A considerable amount of prediction models for different types of concrete are proposed. For instance, Zhang et al.[30] propose a micromechanical model for early-age AS prediction of concrete based on the results of IRH. Wei et al.[31] reveal that the AS occurs when the IRH of concrete drops to about 96%, and the AS and IRH of concrete IC by prewetted lightweight fine aggregates (LWFAs) are in a linear relationship. Jiang et al.[4] establish the correlation between AS and IRH of high-performance cement pastes based on the test results. The previous models are of great significance in predicting the AS of concrete. However, no previous study has investigated the prediction model of AS based on the results of IRH for concrete IC by SAPs considering the effect of *w*/*c* ratio. The objectives of the present study were to investigate the effect of *w*/*c* ratio on AS and IRH of concrete IC by SAPs, and to explore the correlation between AS and IRH of that considering different *w*/*c* ratios. Mechanical properties, IRH, temperature, expansion, and AS of concrete were measured simultaneously. A two-stage prediction model of AS based on the results of IRH of concrete IC by SAPs considering the effect of *w*/*c* ratio was proposed.

2 | EXPERIMENTAL PROGRAM

2.1 | Materials and mixture proportions

Portland cement (Cement II 52.5R) was utilized conforming to Chinese Standard GB 175[34] and ASTM C150,[35] and Table 1 depicts the physical and chemical properties of the cement. The natural river sand with a fineness modulus of 1.83 and a maximum particle size of 1.5 mm was utilized as fine aggregate. The crushed limestone with a maximum particle size of 20 mm and an apparent density of 2660 kg/m^3 was utilized as coarse aggregate. A kind of liquid polycarboxylate-based superplasticizer was utilized to adjust the workability of concrete mixtures. SAPs with a dry-bulk density of 850 kg/m^3 and particle diameters ranging from 125 to 150 μm under dry conditions were utilized in the present study, as depicted in Figure 1. Cement powder, dry SAPs, and oven-dried aggregates were premixed for 30 s before adding the first half of water to ensure the uniform dispersion of SAPs in the mixture. The superplasticizer and the other water were added after 120 s of mixing. The total time of mixing was 5 min.

The ratio of internal curing water provided by SAPs or mixing water to cement was defined as internal curing *w*/*c* ratio or *w*/*c* ratio, as reported in study.[25] Mixtures IC by SAPs with different *w*/*c* ratios (0.33, 0.40, and 0.50) were prepared as Mixture IC33-04, IC40-04, and IC50-04, respectively. To reveal the internal curing effect of the SAPs used in the present study on the IRH and AS of concrete, an ordinary concrete mixture with *w*/*c* ratio of

TABLE 1 Physical and chemical properties of Portland cement

Item	Unit	Portland cement
SiO_2	%	19.90
Al_2O_3	%	4.60
Fe_2O_3	%	3.00
CaO	%	64.60
MgO	%	0.78
SO_3	%	2.37
Na_2O	%	0.06
K_2O	%	0.65
Cl^-	%	0.01
Loss on ignition	%	3.11
Specific surface area	m^2/kg	375
Compressive strength, 3 days	MPa	36.4
Compressive strength, 28 days	MPa	66.9
Initial setting time	min	168
Final setting time	min	226

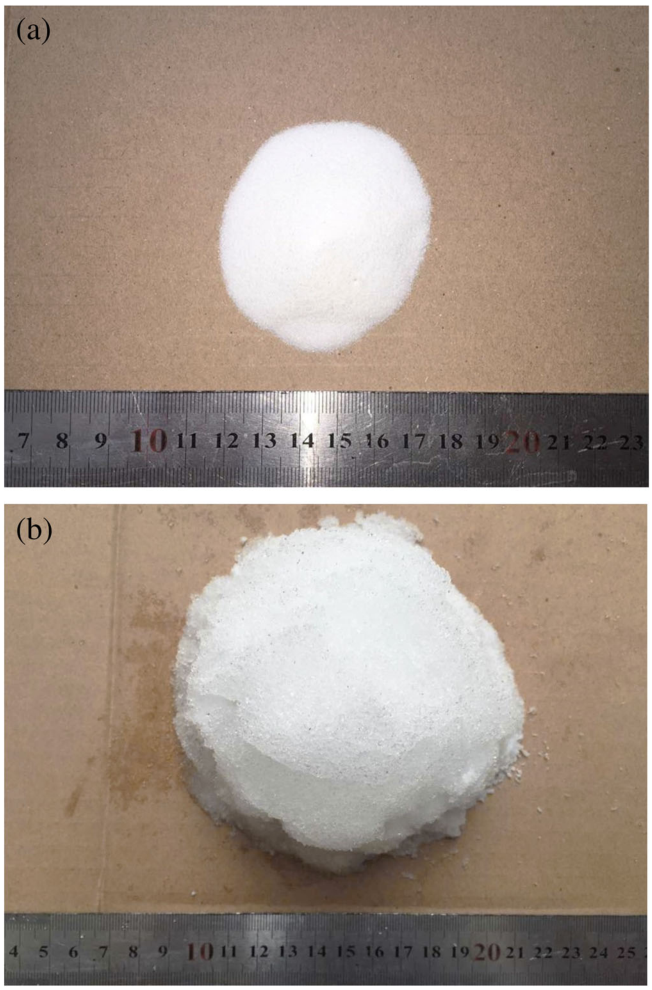

FIGURE 1 SAPs utilized in the present study: (a) collapsed; (b) swollen

TABLE 2 Compositions and properties of mixtures

Mixture composition	RC33-00	IC33-04	IC40-04	IC50-04
w/c	0.33	0.33	0.40	0.50
Water, kg/m^3	171	171	205	256
Cement, kg/m^3	512	512	512	512
Fine aggregate, kg/m^3	636	636	624	606
Coarse aggregate, kg/m^3	1131	1131	1109	1076
SAP, kg/m^3	0	1.77	1.77	1.77
Internal curing water, kg/m^3	0	23.00	23.00	23.00
w_{ic}/c	0	0.04	0.04	0.04
Superplasticizer, kg/m^3	3.3	3.3	1.8	0.8
Slump, mm	100	111	110	111

0.33 was prepared as RC33-00. Table 2 depicts the compositions and properties of mixtures. The ratio of total water to cement is defined as total w/c ratio, which is calculated by Equation (1).[36]

$$w_t/c = w_e/c + w_{ic}/c \tag{1}$$

in which w_t/c is the total w/c ratio; w_e/c is the effective w/c ratio; and w_{ic}/c is the internal curing w/c ratio. The Mixture RC33-00 was not IC by SAPs, and its total w/c ratio was 0.33. The internal curing w/c ratio was constant (0.04) for three mixtures, and the total w/c ratio was 0.37, 0.44, and 0.54 for Mixture IC33-04, IC40-04, and IC50-04, respectively. In the present study, w/c ratio was utilized to represent effective w/c ratio.

2.2 | Required internal curing water

The SAPs were utilized to absorb water, and the water absorbed by SAPs was defined as internal curing water in study.[37] The internal curing water is the dosage of water needed for maximum hydration in concrete, which is calculated by Equation (2).[38]

$$V_{wat} = \frac{C_f \cdot CS \cdot \alpha_{max}}{\rho_{wat}} \tag{2}$$

in which V_{wat} is the volume of water needed for maximum hydration per cubic meter of concrete (m^3 water/m^3 concrete); C_f is the dosage of cement per cubic meter of concrete, in kg/m^3; CS is the chemical shrinkage occurring in the process of cement hydration (kg water/kg cement), and a typical conversation value is 0.07 kg water/kg Portland cement hydrated; ρ_{wat} is the density of water (1×10^3 kg/m^3); and α_{max} is the maximum degree of hydration. The value of α_{max} is estimated by Equation (3).[38]

$$\alpha_{max} = \begin{cases} [w/c]/0.36 & ,w/c < 0.36 \\ 1 & ,w/c \geq 0.36 \end{cases} \tag{3}$$

The dosage of water needed for maximum hydration in theory was 32.85, 35.84, and 35.84 kg per cubic meter of concrete for Mixture IC33-04, IC40-04, and IC50-04, respectively. The duration of saturated conditions was 72 h in the present study, and the 72-h absorption value of SAPs was 13 g water/g SAPs, as reported in study.[25] Therefore, the theoretical dosage of SAPs needed for maximum hydration was 2.53, 2.76, and 2.76 kg per cubic meter of concrete for Mixture IC33-04, IC40-04, and IC50-04, respectively. To better investigate the effect of w/c ratio on concrete IC by SAPs, the dosage of SAPs incorporated to three mixtures was 1.77 kg per cubic meter of concrete (i.e., $w_{ic}/c = 0.04$), as depicted in Table 2.

2.3 | IRH and AS measurements

A testing device was utilized to test IRH and AS simultaneously on the concrete specimens with the dimension of 100 mm × 100 mm × 550 mm, and average value of three tested specimens for each mixture was utilized in the present study. A polyvinyl chloride (PVC) tube was inserted in the center of concrete specimen after pouring, and a small stick was inserted into the PVC tube. A digital resistance-based sensor, which could measure IRH and temperature of concrete simultaneously, was utilized to replace the small stick in the PVC tube, and the values of IRH and temperature of concrete were obtained after the sensor was connected to the data acquisition system. The concrete specimens were under sealed condition.

In the present study, a non-contact method was utilized to measure AS of concrete, which made the test start at the time when the concrete specimen formed. When the AS was measured, the ambient temperature

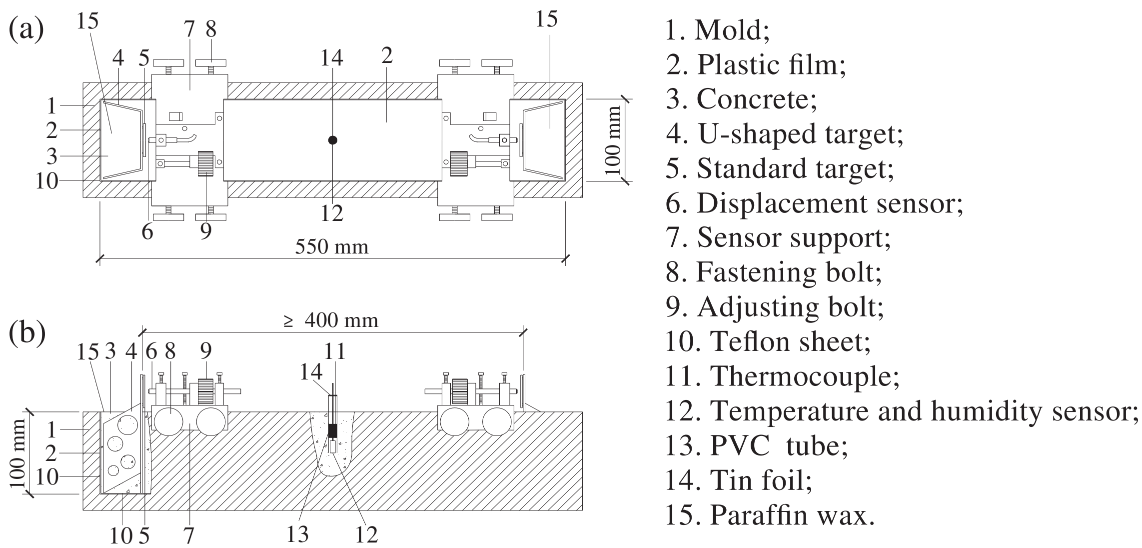

FIGURE 2 Specimen size and arrangements of sensors in specimen: (a) top view; (b) side view

and humidity of the curing room were also measured simultaneously. The strain measured in the concrete specimen was in one direction, and the test results were recorded every 15 min. Figure 2 depicts specimen size and arrangements of sensors.

Teflon sheets were covered on the bottom and two sides of the mold to reduce the friction resistance between concrete and mold, and then a layer of plastic film was laid on the sheets. Two U-shaped targets were placed on both sides of the mold, and the measuring planes of the targets were kept perpendicular to the bottom of the mold during the process of pouring and vibrating concrete. The concrete specimen was sealed with plastic film after pouring, and a PVC tube with an inner diameter of 10 mm was inserted in the center of specimen. To prevent mortars from entering the tube and make preparation for the measurement of IRH, a small stick with an outer diameter of 10 mm was inserted into the PVC tube. All the specimens were cured at a constant temperature of $20 \pm 2^{\circ}$C and relative humidity of $65 \pm 5\%$ RH. A standard target was placed on the U-shaped target, and then the displacement sensor was fixed through adjusting the fastening bolt. The probe of the displacement sensor was aimed at the standard target, and was adjusted through the adjusting bolt to the suitable measuring position. To prevent the water evaporation, the PVC tube was sealed with tin foil and the U-shaped targets were sealed with paraffin wax. The small stick was replaced with the digital resistance-based sensor after the final setting time of concrete, and make sure that the bottom of the sensor was in contact with the concrete. Three rubber sealing rings were uniformly sheathed on the sensor, and the exposed end of PVC tube was sealed with tin foil to avoid environmental disturbance. The data acquisition system started after the installation of the testing device. Figure 3 depicts the photos of IRH and AS measurements of mixtures.

Additional tests of setting time and 28-d compressive strength were conducted conforming to Chinese Standards GB 50080[39] and GB 50081,[40] as reported in study,[41] and the results are depicted in Table 3.

3 | TEST RESULTS AND DISCUSSION

3.1 | Effect of *w/c* ratio on IRH of IC concrete

The IRH of IC concrete was mainly affected by self-desiccation when the concrete specimen was under sealed condition. Figure 4 depicts the correlation between IRH and age of mixtures. The IRH of concrete increased with the addition of SAPs, and the IRH of IC concrete increased as increase of *w/c* ratio. The development of IRH experienced two stages: a water-vapor saturated stage with 100% RH (stage I), and a stage in which IRH decreased gradually (stage II). Similar results can be found in study.[42] Figure 4 depicts that IRH decreased with age. The 21-d IRH of concrete was 91.3%, 96.7%, 98.3%, and 99.1% RH, and the 28-d IRH of concrete was 88.7%, 95.2%, 97.1%, and 98.1% RH for Mixture RC33-00, IC33-04, IC40-04, and IC50-04, respectively. Compared to Mixture RC33-00, the addition of SAPs significantly increased the IRH in the Mixture IC33-04. This suggested that the pre-soaked SAP released water to the concrete,

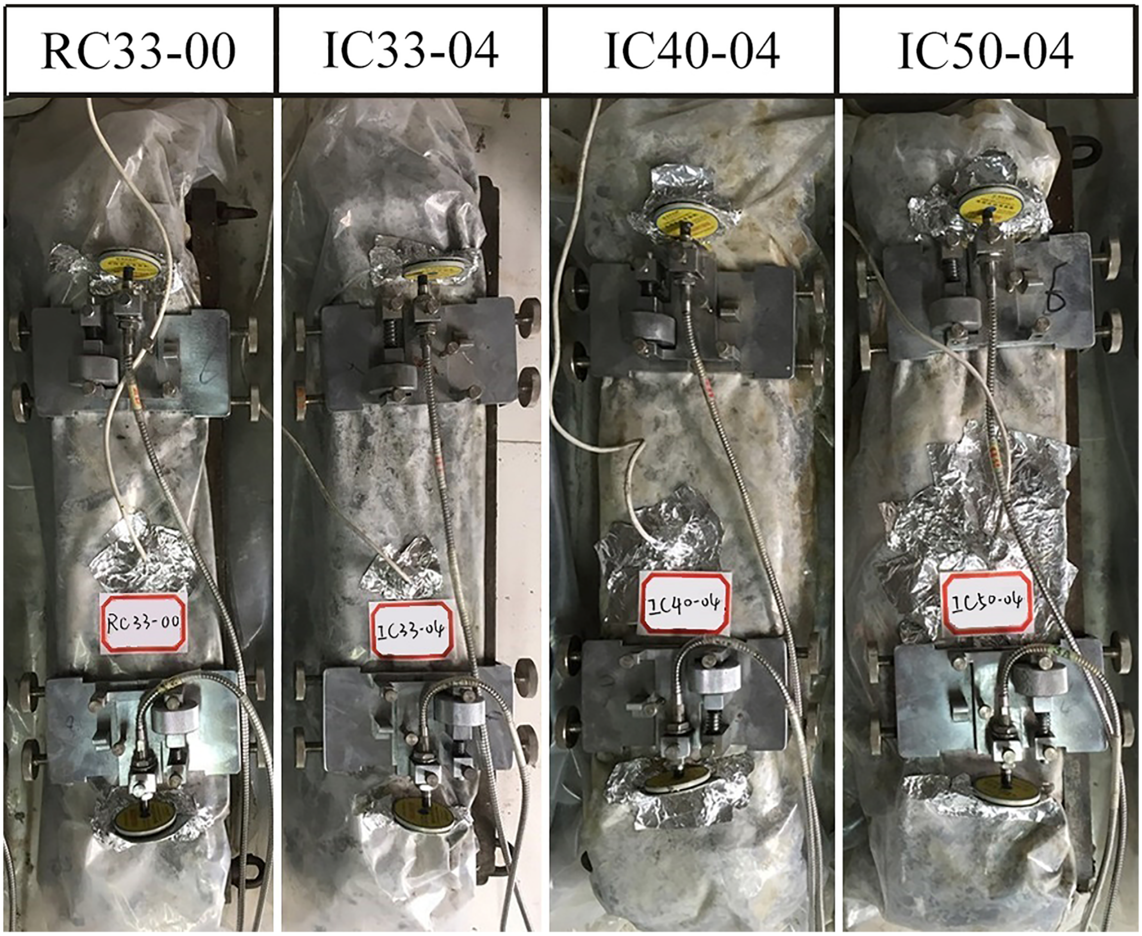

FIGURE 3 Photos of IRH and AS measurements of mixtures

TABLE 3 Setting time and 28-d compressive strength of mixtures

Concrete mixtures	w/c	Curing temperature (°C)	Initial setting time (h)	Final setting time (h)	28-d compressive strength (MPa)
RC33-00	0.33	20 ± 2	6.1	8.3	65.4
IC33-04	0.33		6.9	9.3	54.7
IC40-04	0.40		7.1	9.4	49.8
IC50-04	0.50		7.4	9.5	45.4

which increased the IRH in IC concrete. This finding was also reported in study.[25] Results also reveal that the increase of w/c ratio both increased the IRH of concrete. Similar results can be found in studies.[42,43] The results may be explained by the fact that the IRH variation of concrete under sealed condition is mainly caused by self-desiccation.[43] As a multiphase system, the pores in concrete formed by aggregates and cement particles are full of liquid water, gas mixture, and water vapor.[42] The particles of cement are dispersed in the water inside the concrete after pouring, and space occupied by liquid water is gradually filled with hydration products with high volume during the process of hydration. Therefore, the liquid water in pores of concrete is reduced, and the concrete becomes dense gradually. The size as well as the amount of pores is decided by the w/c ratio.[42] Concrete mainly includes four kinds of pores: gel pores, transitional pores, capillary pores, and macro pores.[44] More pores with large diameter as well as higher porosity can be found in the concrete with higher w/c ratio, and more liquid water can be found in the pores of concrete with higher the w/c ratio. Therefore, compared with

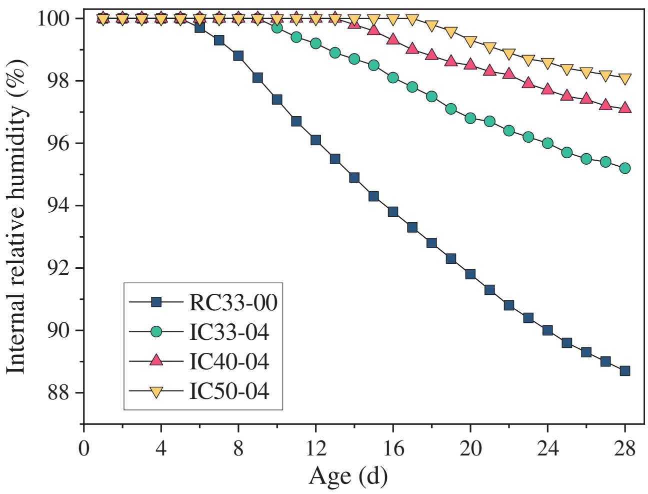

FIGURE 4 Correlation between IRH and age of mixtures

concrete with lower *w*/*c* ratio, the IRH of concrete with higher *w*/*c* ratio was higher at same age. Besides, water loss rate was considered to be same for the mixtures because the concrete specimens were all sealed and cured under the same environmental condition in the present study, thus, the reduction of IRH was lower in the concrete with higher *w*/*c* ratio.

3.2 | Effect of *w*/*c* ratio on critical time of IC concrete

The pores in concrete were mostly filled with liquid water at the very early age of concrete after pouring, which made the IRH of concrete was 100%. The duration of stage I with 100% RH was defined as the critical time, which lasted for a long time due to the slow rate of water consumption, as reported in study.[45] When the dosage of water decreased to a critical value due to cement hydration, the vapor pressure decreased, which caused the reduction of IRH in concrete, and meant that concrete went into stage II. The critical time was 6.3, 10.5, 14.4, and 18.2 d for Mixture RC33-00, IC33-04, IC40-04, and IC50-04, respectively. The critical time of concrete increased by 66.67% with the addition of SAPs (0.35% by weight of cement), which matched the results observed in study.[19] Results also reveal that the critical time of IC concrete increased by 37.14%, and 73.33% as increase of *w*/*c* ratio ranging from 0.33 to 0.40, and 0.50, respectively. Similar results can be found in study,[42] which reveals that the length of the critical time of high strength concrete with a low *w*/*c* ratio (around 0.33) is shorter than that of normal strength concrete with a high *w*/*c* ratio (around 0.52). The initial dosage of water in pores as well as water loss rate affects the development of IRH. The initial size as well as amount of pores in the concrete is affected by *w*/*c* ratio. More large pores filled with liquid water and more initial dosage of water can be found in the concrete with higher *w*/*c* ratio. Therefore, for the same water loss rate, the critical time of concrete increased as increase of *w*/*c* ratio.

3.3 | Effect of *w*/*c* ratio on temperature and expansion of IC concrete

The temperature variation inside the concrete may cause thermal strain, and affect the hydration and self-desiccation at early age, which may further affect the AS of concrete.[46] The concrete was cured in the curing room at a constant temperature, however, the temperature inside the concrete was different. The temperature peak was 26.01, 26.37, 25.41, and 24.93°C for Mixture RC33-00, IC33-04, IC40-04, and IC50-04 at 12, 12, 14, and 15 h, respectively, as depicted in Figure 5. Compared with Mixture RC33-00, the temperature peak of IC33-04 increased slightly with the addition of SAPs. The addition of SAPs has contributed to enhancing the degree of hydration of the cement, which results in higher temperature peak in concrete.[47] Results also reveal that the temperature peak of IC concrete decreased as increase of *w*/*c* ratio. Similar results can be found in studies.[48,49] A possible explanation for this might be that increase of *w*/*c* ratio slows down the increasing rate of Ca^{2+} concentration in the cement pore solution, which may increase the induction period of hydration and slightly decrease the hydration peak.[48] Another possible explanation for this is that the degree of dilution of cement in the cement–water solution increases as increase of *w*/*c* ratio, which suppresses hydration rate, and reduces hydration heat.[49]

The determination of starting point for the measurement of AS is important. In the present study, initial setting time of concrete was taken as starting point for the measurement of AS, which was defined as the macroscopic volume decrease of concrete due to hydration after initial setting, as reported in study.[50] The test result of total deformation measured in the present study included the thermal expansion and AS, and AS is calculated by Equation (4).[51]

$$\varepsilon_{\mathrm{as}}(t) = \varepsilon_{\mathrm{total}}(t) - \alpha(t) \cdot [T(t) - T_0] \tag{4}$$

in which $\varepsilon_{\mathrm{as}}(t)$ is the AS at t d, in με; $\varepsilon_{\mathrm{total}}(t)$ is the total measured strain at t d, in με; $\alpha(t)$ is the thermal expansion coefficient of concrete, in με/°C; $T(t)$ is the temperature of concrete at t d, in °C; T_0 is the initial temperature of concrete, in °C; and t is the age of concrete, in d. Considering that the dimension of the specimen

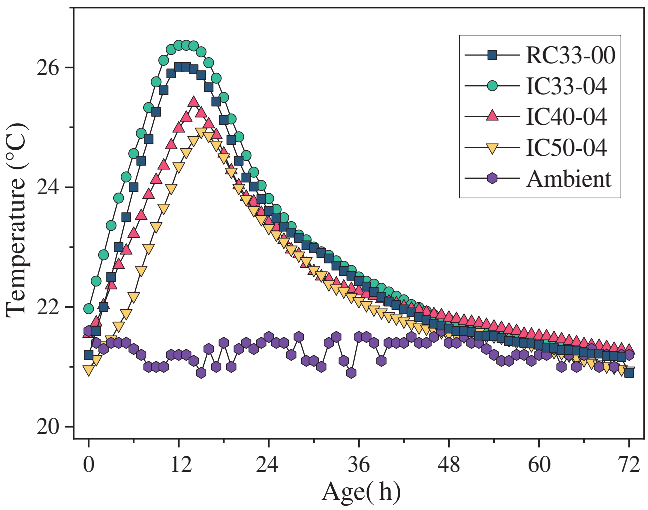

FIGURE 5 Temperature history of mixtures in the first 3 days

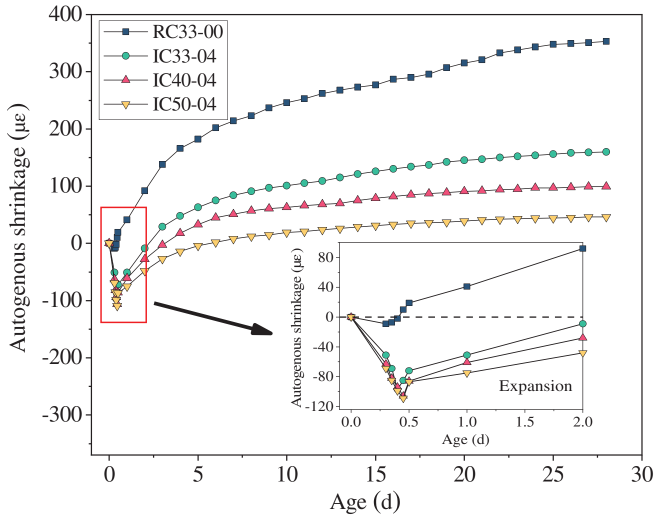

FIGURE 6 Correlation between AS and age of mixtures

was small, temperature gradient difference between the center and surface of concrete was ignored. The AS was corrected for thermal strain by assuming that the thermal expansion coefficient was 10 με/°C, as reported in study.[52]

Figure 6 depicts AS of four mixtures, and positive or negative strain indicates that the concrete is in the state of shrinkage or expansion, respectively. The development of AS of IC concrete could be divided into three stages, as reported in study.[53] The concrete was in the expansion stage after setting, and then the concrete entered the initial shrinkage stage, in which the development of AS was fast. The development of AS slowed down after a few days (about 7 d), and the concrete entered the stable shrinkage stage. An expansion after setting was also exhibited in studies.[54,55]

In the present study, the Mixture RC33-00 slightly expanded by 9 με after the initial setting, and the addition of SAPs significantly increased the expansion peak of Mixture IC33-04. Similar results can be found in study.[53] Results also reveal that the expansion peak increased as increase of *w*/*c* ratio. The absolute value of expansion peak was 97, 106, and 109 με for Mixture IC33-04, IC40-04, and IC50-04, which increased by 9.28%, and 12.37% as increase of *w*/*c* ratio ranging from 0.33 to 0.40, and 0.50, respectively. There are several possible explanations for the results. Firstly, the expansion is probably caused by the formation of $Ca(OH)_2$ with large size during the hydration of cement.[55] A crystallization pressure on the walls of pores is created due to the development of crystal, which can cause the expansion of the microstructure by increasing porosity in the concrete.[54] The addition of SAPs and the increase of *w*/*c* ratio increase size of crystal, which increases the expansion of concrete. Secondly, C—S—H rims develop surrounding the residual unreacted cement cores in the concrete due to hydration reaction, and the portions of anhydrous grains in concrete are replaced by C—S—H rims with higher volume. Thickness of C—S—H rims increases as increase of *w*/*c* ratio, which results in higher expansion peak of concrete with higher *w*/*c* ratio.[55] Thirdly, addition of SAPs promotes the formation of hydroxide in concrete, and makes the IC concrete have a larger expansion value than reference concrete,[56] and the existence of expansion stage in IC concrete is important in decreasing AS compared with the reference concrete.[54]

3.4 | Effect of *w*/*c* ratio on shrinkage of IC concrete

The concrete entered the shrinkage stage after expansion, and the time for Mixture RC33-00, IC33-04, IC40-04, and IC50-04 to enter the shrinkage stage was 0.4, 3.5, 4.6, and 7.2 d, respectively. The main reason was that the absolute value of expansion peak increased and the AS rate decreased with the addition of SAPs and the increase of *w*/*c* ratio, as depicted in Figure 6. The net shrinkage was defined as the difference between maximum and minimum autogenous deformation in study,[57] which meant that the early-age shrinkage started from the time of expansion peak of concrete. The net shrinkage was taken to evaluate the autogenous deformation of concrete in studies.[36,57] Figure 7 depicts the correlation between net shrinkage strain and age of mixtures. The AS of IC concrete decreased with that addition of SAPs and the increase of w/c ratio. The net AS of mixtures at 3, 7, 14, 21, and 28 d is depicted in Table 4. For instance, the 28-d net AS was 362, 257, 205, and 155 με for Mixture RC33-00, IC33-04, IC40-04, and IC50-04, respectively. Results reveal that the 28-d net AS of Mixture RC33-00 decreased by 29.01% with the addition of SAPs with a dosage of 0.35% by weight of cement. However, the AS was not eliminated when the dosage of SAPs reached 0.35% by weight of cement in the present study. The efficiency of internal curing is mainly affected by the availability of internal curing water, which is influenced by the particle size of SAP as well as the spacing between SAP particles,[58] and the actual efficiency of many types of SAP was not complete. The AS is also not eliminated in study[59] with the amount of internal curing water of 50 kg/m^3. A possible explanation for this might be that the water fails to move freely in the concrete, which makes that the required amount of internal curing water calculated in theory was underestimated than the actual amount in need.[59]

Besides, the 28-d net AS of IC concrete decreased by 20.23%, and 39.69% as increase of w/c ratio ranging from 0.33 to 0.40, and 0.50, respectively. Similar results can be found in studies.[4,8] Li et al.[44] reveal that AS is mainly influenced by gel pores as well as transitional pores. The pressure in these pores increases as the humidity in the pores decreases, which increases the shrinkage stress on the walls of pores, and finally increases the AS of concrete. Therefore, there are several possible explanations for the result of AS. Firstly, more water is supplied by concrete with higher w/c ratio, and additional water is released by SAPs in concrete, both of which increase the IRH of concrete, and decrease the capillary pressure in concrete.[7,42] Secondly, porosity as well as mean pore radius in concrete increases as increase of w/c ratio,[44,60] and lower capillary pressure is created in the pore water of concrete. Therefore, the AS of IC concrete decreases as increase of w/c ratio. Results also reveal that AS of IC concrete increases with age. Similar results can be found in studies.[55,61] The main reason for the results is that the IRH of concrete decreases due to the hydration reaction, which induces a great amount of pores in the hardened concrete and decreases the dosage of water in pores. Capillary tension increases when the saturation state of capillary pore changes from saturated to unsaturated, which induces the AS in concrete.[62]

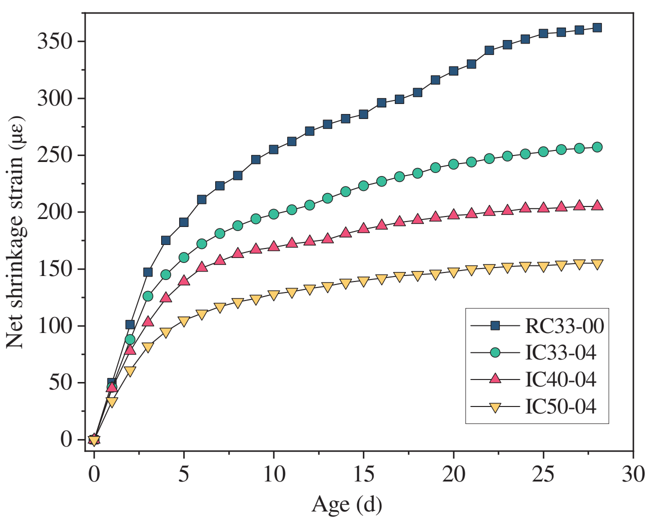

FIGURE 7 Correlation between net shrinkage strain and age of mixtures

The development of AS is directly affected by the AS rate, which is calculated by Equation (5).[63]

$$R(t) = \frac{d\varepsilon_{as}(t)}{dt} \quad (5)$$

in which $R(t)$ is the AS rate at t d, in με/d; and ε_{as} is the AS at t d, in με.

The AS rate of Mixture RC33-00, IC33-04, IC40-04, and IC50-04 is depicted in Table 5, respectively. The results reveal that the addition of SAPs with a dosage of 0.35% by weight of cement decreased the AS rate of Mixture IC33-04 compared to Mixture RC33-00, and the AS rate of Mixture IC33-04, IC40-04, and IC50-04 decreased as increase of w/c ratio. AS rate of all mixtures was less than 10 με/d after the age of 14 d, which decreased significantly compared with that at an earlier age. The values of AS rate of four mixtures were small at the age of 28 d,

TABLE 4 Net autogenous shrinkage of mixtures at different ages

		Autogenous shrinkage (με)				
Concrete mixtures	***w/c***	**3 d**	**7 d**	**14 d**	**21 d**	**28 d**
RC33-00	0.33	147	223	282	330	362
IC33-04	0.33	126	181	218	244	257
IC40-04	0.40	103	157	181	198	205
IC50-04	0.50	82	117	138	150	155

TABLE 5 Autogenous shrinkage rate of mixtures at different ages

	Autogenous shrinkage rate (με/d)			
Age (d)	RC33-00	IC33-04	IC40-04	IC50-04
1	51	44	39	31
3	37	29	23	17
5	18	14	13	8
7	14	8	6	5
14	5	6	5	3
21	9	3	2	2
28	2	1	1	1

and the development of AS tended to be stable. Similar results can be found in study,[8] which reveals that the AS of all mixtures reached 80% of 28-d shrinkage at the age of 14 d, and the results indicate that the AS of IC concrete is mainly concentrated at the early stage. The main reason was that when the IC concrete was at early age, the mechanical properties of concrete were still at the development stage, elastic modulus was low, and creep coefficient was high. However, the development rate of internal hydration was fast, which caused great self-desiccation and made the AS develop faster than that of later stage.

Considering that the development of IRH in concrete experiences two stages,[42] a two-stage prediction model considering the effect of w/c ratio is necessary for better predicting AS of concrete based on the results of IRH. Based on experiment results and prediction model in study,[30] the following two-stage prediction model of AS on early-age IC concrete was proposed in the present study.

$$\varepsilon_{\mathrm{as}}=\begin{cases}\eta\left(1-\sqrt[3]{1-(V_{\mathrm{CS}}-V_{\mathrm{CS0}})}\right) & ,\mathrm{RH}=100\% \\ \varepsilon_{\mathrm{cs}}\quad -k\ln(\mathrm{RH})+b & ,\mathrm{RH}<100\%\end{cases} \tag{6}$$

in which η is the influencing factor of stiffness; V_{CS} is the chemical shrinkage, in με; V_{CS0} is the chemical shrinkage (in volume) after concrete setting, in με; k,b are the influencing factors. Considering that the AS of concrete is mainly caused by chemical shrinkage during the water-vapor saturated stage with 100% RH (stage I), the chemical shrinkage V_{CS0} is ignored for simple calculation. The results of V_{CS} is calculated by Equation (7).[26]

$$V_{\mathrm{CS}}=0.2(1-p)\alpha \tag{7}$$

TABLE 6 Influencing factors of mixtures

Influencing factor	IC33-04	IC40-04	IC50-04
t_{k}	1.511	1.501	1.492
q	1.241	1.250	1.268
η	0.0073	0.0062	0.0055

in which p is the initial porosity, $p=\frac{w/c}{w/c+\rho_{\mathrm{w}}/\rho_{\mathrm{c}}}$, w/c was the effective w/c ratio; and α is the cement hydration degree.

Cement hydration degree is calculated by Equation (8).[45]

$$\alpha=\alpha_{\max}e^{-\left(\frac{t_{\mathrm{k}}}{t}\right)^{q}} \tag{8}$$

in which t_{k},q are the influencing factors. According to the experiment results, the regression analysis of the influencing factors for four mixtures was carried out, and the results are depicted in Table 6.

The influencing factors depicted in Table 6 were all related to w/c ratio, and results of regression analysis of influencing factors and w/c ratio at stage I are given in Equation (9).

$$\begin{cases}t_{\mathrm{k}}=1.5472e^{-0.073(w/c)} \\ q=1.1890e^{-0.128(w/c)} \\ \eta=0.0123e^{-1.633(w/c)}\end{cases} \tag{9}$$

The IRH decreased gradually due to the development of hydration in IC concrete with SAPs, which meant that the concrete entered stage II. The capillary pressure is the main cause of AS in concrete at stage II.[19,53] The AS and logarithm of RH were in a linear relationship according to the Kelvin-Laplace equation, and the fitting results of the data are depicted in Figure 8. Results reveal that when reduction of IRH was the same, the increase of AS decreased as increase of w/c ratio.

At stage II, results of regression analysis on influencing factors and w/c ratio are given in Equation (10).

$$\begin{cases}k=-4045(w/c)+2595 \\ b=-18641(w/c)+11960\end{cases} \tag{10}$$

Substituting Equations (7) and (8) into Equation (6) and combining Equations (2), (8), (9), and (10), the prediction model of AS based on the results of IRH of IC concrete considering the effect of w/c ratio was proposed, as depicted in Equations (11) and (12).

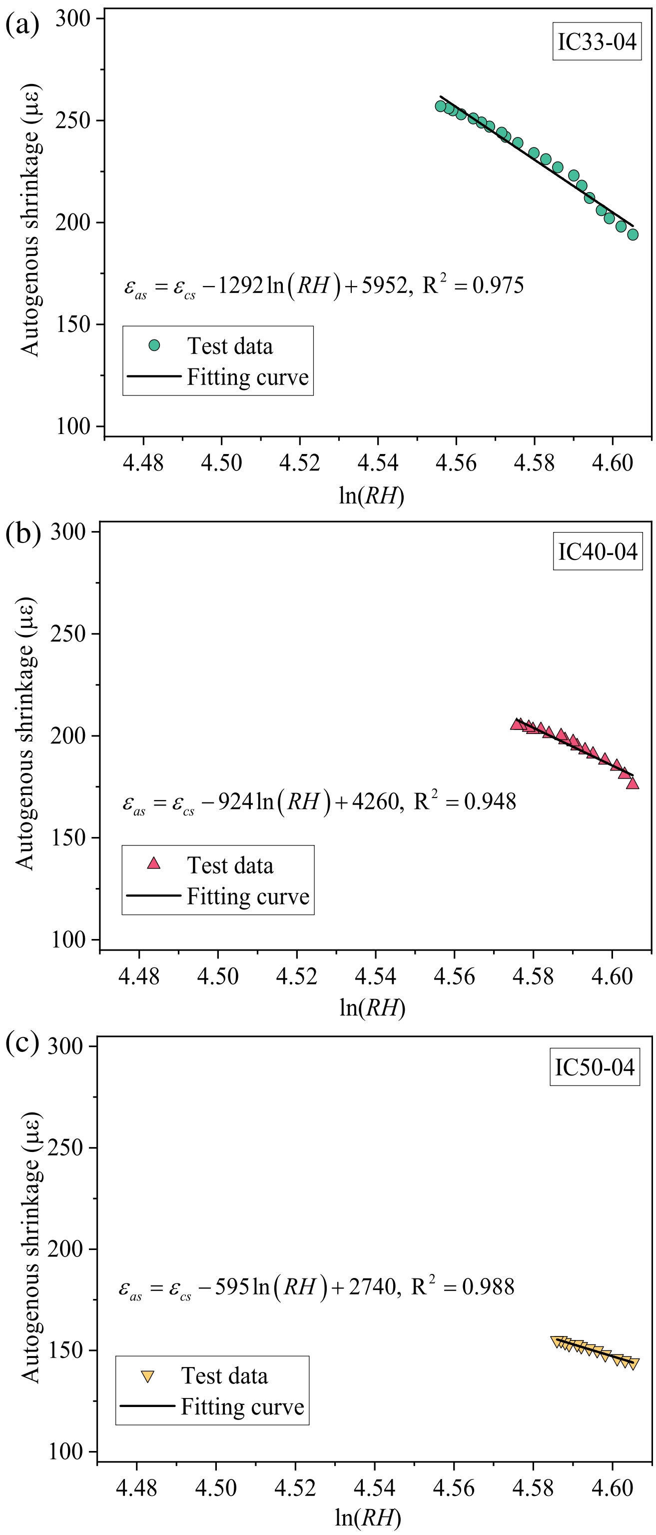

FIGURE 8 Correlation between AS and ln(*RH*) of mixtures

$$\varepsilon_{\mathrm{as}} = \begin{cases} \eta\left(1-\sqrt[3]{1-\left(0.2\left(1-\dfrac{w/c}{w/c+\rho_{\mathrm{w}}/\rho_{\mathrm{c}}}\right)\alpha_{\max}e^{-\left(\frac{t_{\mathrm{k}}}{t}\right)^{q}}\right)}\right) & ,\mathrm{RH}=100\% \\ \varepsilon_{\mathrm{cs}} - k\ln(\mathrm{RH}) + b & ,\mathrm{RH}<100\% \end{cases} \quad (11)$$

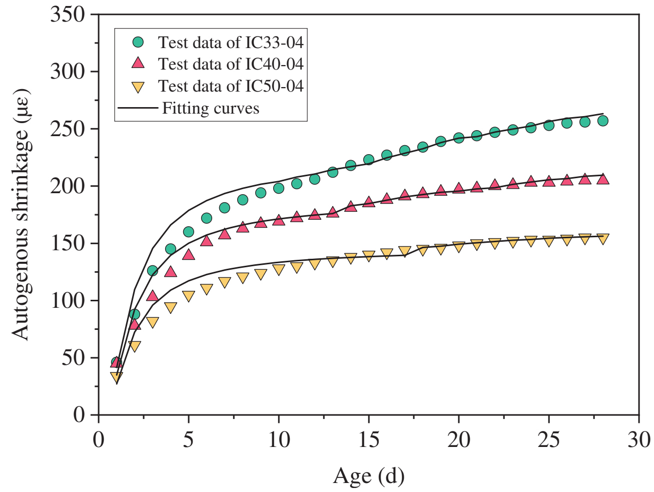

FIGURE 9 Comparison between results of prediction model and experiment

$$\begin{cases} \alpha_{\max} = \begin{cases} [w/c]/0.36 & ,w/c<0.36 \\ 1 & ,w/c\geq 0.36 \end{cases} \\ t_{\mathrm{k}} = 1.5472e^{-0.073(w/c)} \\ q = 1.1890e^{-0.128(w/c)} \\ \eta = 0.0123e^{-1.633(w/c)} \\ k = -4045(w/c)+2595 \\ b = -18641(w/c)+11960 \end{cases} \quad (12)$$

The comparison between the results of the prediction model and the experiment is depicted in Figure 9. Results reveal that the early-age AS of four mixtures was in good agreement with fitting results, and a two-stage prediction model was able to effectively predict AS of IC concrete with different *w*/*c* ratios ranging from 0.33 to 0.50 based on the results of IRH. Although the effect of w/c ratio on AS and IRH of the concrete IC by SAPs, and the internal curing effect of SAPs on the concrete with *w*/*c* ratio of 0.33 were investigated in the present study, further studies on the internal curing effect of SAPs on the concrete with high *w*/*c* ratios are necessary for better understanding the correlation between AS and IRH of IC concrete with different *w*/*c* ratios.

4 | CONCLUSIONS

Effect of *w*/*c* ratio on the IRH and AS of IC concrete was investigated in the present study. Tests and analysis on IRH, temperature, expansion, and shrinkage of concrete for Mixture IC33-04, IC40-04, and IC50-04 were conducted, respectively. The properties of an ordinary concrete mixture with *w*/*c* ratio of 0.33 (Mixture RC33-00) was tested simultaneously. Based on the experiment findings, the following conclusions were obtained:

1. The IRH of IC concrete increased as increase of *w*/*c* ratio, and the IRH of concrete increased with the addition of SAPs. The development of IRH experienced two stages: a water-vapor saturated stage with 100% RH (stage I), and a stage in which IRH decreased gradually (stage II). A two-stage prediction model of AS based on the results of IRH for IC concrete considering the effect of *w*/*c* ratio was proposed.
2. The critical time increased as increase of *w*/*c* ratio, and the critical time of concrete increased by adding SAPs.
3. The expansion peak of IC concrete increased as increase of *w*/*c* ratio. The addition of SAPs significantly increased the expansion peak of concrete.
4. The AS and AS rate of IC concrete decreased as increase of *w*/*c* ratio. The AS and AS rate of concrete decreased by adding SAPs.

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DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the published article.

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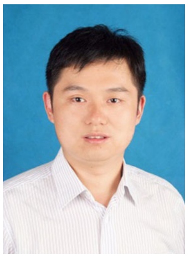

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