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Exploration of structural modeling techniques for mechanical properties and durability of composite concrete

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Abstract The durability problem of composite concrete structures is becoming more and more serious, and in line with the development trend of BIM technology, BIM technology is applied to assess the durability of concrete structures. In this paper, mechanical property tests and durability tests were conducted by making test specimens of RRCM composite concrete and C40 ordinary concrete with different mix ratios, respectively. For the first time, a quantitative BIM modeling and analysis method for durability of RRCM composite concrete structures is proposed. The factors affecting the structural durability were explored from the aspects of environment, materials and components respectively, and the carbonation depth of concrete and corrosion of steel reinforcement were calculated with the influence of components as the main focus. Taking the carbonation depth, concrete strength, and crack width as the durability quantitative analysis indexes, we input all the data related to the composite concrete structure into the BIM model, and analyze the durability of the composite concrete structure quantitatively by using the comprehensive durability evaluation matrix. The analysis results show that the RRCM composite concrete we designed has an ultimate tensile strength of 4105 kN in terms of mechanical performance, and the flexural strength is significantly improved compared with ordinary C40 composite concrete. The maximum error between our proposed BIM modeling technique and the actual measured carbonation depth in the carbonation test was 7.27% ≤ 10%, indicating that the method can be used for the assessment of carbonation of composite concrete. In the reinforcement corrosion test, the maximum error between the measured and actual measured reinforcement corrosion rate was 28.13% ≤ 30%, indicating that the method can be used for reference in the durability calculation of actual projects.

Index Terms composite concrete, structural durability, proportioning, BIM modeling, mechanical properties

I. Introduction

Composite concrete is a new type of high-tech concrete, is a substantial improvement in the performance of ordinary concrete based on the use of modern concrete technology to produce concrete. It takes durability as the main index of design, and focuses on the following properties to ensure the requirements for different purposes: durability, workability, applicability, strength, volume stability and economy [1]-[4].

Mechanical properties of concrete refers to the strength and deformation capacity of concrete materials, of which the strength includes compressive strength, tensile strength, shear strength and bending strength. The deformation capacity includes modulus of elasticity, Poisson's ratio, stiffness, etc [5]-[8]. The mechanical properties of concrete is one of the most basic and important considerations in the design and use of materials, which directly determines the bearing capacity and safety performance of concrete structures. Therefore, in the selection of concrete materials and the design of concrete structures, the influence of its mechanical properties should be fully considered [9]-[12]. The durability of concrete refers to the persistence and durability of concrete under long-term use and environmental effects. The durability of concrete is mainly affected by the following factors: porousness of concrete, water content, chloride ions, acidity and alkalinity, freezing and thawing cycles, and temperature changes [13]-[16]. Different environmental factors can affect the durability of concrete in different ways. Therefore, the effects of mechanical properties and durability of concrete need to be considered comprehensively during the design and use of concrete structures to ensure the safety and durability of concrete structures [17]-[20].

The traditional structural durability assessment method of composite concrete requires the cooperation of multiple precision instruments for measurement, which has the disadvantages of high cost and long cycle time. The innovation of this paper lies in the first application of BIM modeling analysis method to the structural durability assessment of composite concrete, i.e., quantitative analysis indexes affecting structural durability such as carbonation depth, concrete strength, crack width, etc., as well as data related to the composite concrete structure are inputted into the BIM model, and the structural durability of composite concrete is quantitatively analyzed by using the comprehensive durability assessment matrix. Meanwhile, the second innovation of this study is to design a new type of composite concrete that utilizes Rapidly Repair Cement Material (RRCM) material as the interfacial agent of concrete, and the mechanical properties and durability of the new RRCM composite concrete were tested through a series of test methods.

II. Experimental design

Reasonable determination of the dosage of four materials: cement, water, sand and stone in proportion to the relationship between the design of the composite concrete ratio directly determines the quality of the concrete structure. In this chapter, the mix ratio test was conducted on the test raw materials, and the composite concrete test specimens required in the subsequent chapters were prepared, and the mechanical property test was conducted at the same time. In addition, the quantitative BIM modeling and analysis method of composite concrete structure durability is proposed for the problem that the index value of composite concrete is far from the measured value. The factors affecting structural durability are explored from the aspects of environment, materials and components respectively, and the carbonation depth of concrete and the corrosion of steel reinforcement are calculated with the influence of components as the main focus. Taking carbonation depth, concrete strength, and crack width as the quantitative durability analysis indexes, all the data related to composite concrete structures are input into the BIM hierarchical architecture, and the durability of composite concrete structures is quantitatively analyzed by using the comprehensive durability assessment matrix.

II. A. Test raw materials

II. A. 1) Cement

As the most important building material for composite concrete, the quality of cement directly affects the mechanical properties and service life of composite concrete. The mineral composition of cement mainly consists of tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium iron aluminate (C_4AF). The Technical Rules for Construction of Highway Composite Concrete Pavement (JTGTF30-2014) stipulates in the chemical composition of cement that the medium and light traffic pavement should not be less than 15%.

Cement selection must comply with the index requirements specified in Technical Rules for Construction of Composite Concrete Pavements (JTG TF30-2014). For this test, the cement selected is P.O 42.5 cement produced by X Ltd.

II. A. 2) Coarse aggregates

Coarse aggregate plays an important role in composite concrete, which requires very high early compressive and flexural strength. According to the different mix ratios required for making specimens, two kinds of graded aggregates with different grain sizes (5000g each) were selected:

(1) 5~20mm graded gravel.

(2) 20~35mm graded gravel.

The coarse aggregate comes from a local quarry, and the sieve test results of the crushed stone are shown in Table 1.

Table 1: Coarse aggregate sieve analysis

	(5~20mm graded gravel)					
Screen size (mm)	30	20	15	10	5	<5
Sieve allowance (g)	0	307	918	1910	1738	127
Fractional screening margin (%)	0	6.14	18.36	38.2	34.76	2.54
Cumulative screening margin (%)	0	6.14	24.5	62.7	97.46	100
	(20~35mm graded gravel)					
Screen size (mm)	≥37.5	35	30	25	20	<20
Sieve allowance (g)	0	217	1005	1772	1834	172
Fractional screening margin (%)	0	4.34	20.1	35.44	36.68	3.44
Cumulative screening margin (%)	0	4.34	24.44	59.88	96.56	100

II. A. 3) Fine aggregates

Fine aggregate not only plays a filling role for composite concrete, but also can play a bonding role for the interface between coarse aggregate and binder, and at the same time can improve the abrasion resistance of composite concrete.

Fine aggregate is mostly natural sand, whose main requirements are solid texture, clean and less impurities. The fineness modulus and particle grading of sand are important indicators for evaluating its technical properties. The test uses pure natural sand from a property, and its physical property test results are shown in Table 2, and the sieve test results through 2.36~0.15mm sieve holes are shown in Table 3. The fine aggregate totaled 2000g, the fineness modulus was 2.38, and the apparent density reached 2750 kg/m^3 .

Table 2: Physical properties of fine aggregates

Mud content	Water content	Packing density	Apparent density	Fineness modulus
0.6%	1.5%	1620 kg/m^3	2750 kg/m^3	2.38

Table 3: Sieve analysis of fine aggregates

	(5~20mm graded gravel)						
Screen size (mm)	5	2.3	1.2	0.8	0.4	0.2	<2
Sieve allowance (g)	0	408	371	502	381	323	15
Fractional screening margin (%)	0	20.4	18.55	25.1	19.05	16.15	0.75
Cumulative screening margin (%)	0	20.4	38.95	64.05	83.1	99.25	100

II. A. 4) Interfacial agents

Rapidly Repair Cement Material (RRCM) material, as a commonly used interfacial agent, has the main chemical components of cement, sand and water. Its water-cement ratio ranges from 0.3 to 0.5, and the gray-to-sand ratio is generally in the range of 1:1-2.5. The water-cement ratio of the cement mortar used in this test is 0.4, and the gray-to-sand ratio is 1:1.5.

II. B.Test apparatus

(1) X-ray fluorescence spectrometer

The samples were analyzed by Rigaku Ultimate IV X-ray diffractometer for mineral composition and XRD diffraction patterns of composite concrete before and after high temperature calcination, with a scanning angle 2θ ranging from 5° to 90°, a scanning speed of 0.2s/step, a step width of 0.02°, and a wavelength of 1.5512 A. The tests were conducted using a real estate 3600 model of X-ray fluorescence spectrometer (XRF). X-ray fluorescence spectrometer (XRF) of a property to determine the chemical composition of the composite concrete samples.

(2) Fourier transform infrared spectrometer (FTIR)

A Thermo Scientific Nicolet Is5 Fourier Transform Infrared (FTIR) spectrometer was used to measure the infrared absorption spectra of different calcination conditions. The wave number range was 5000-400 cm^{-1} with a scan number of 42 and a resolution of 5 cm^{-1} .

(3) Electron microscope

Tests were conducted to observe the microstructure at different calcination temperatures and conservation times using a Quanta 3D FEG field emission environmental scanning electron microscope (ESEM) from FEI, Germany, with an accelerating voltage of 200V~50kV, an electron beam current of 200 ηA , a magnification of 50~1580000, and an environmental scanning modulus of 20Pa~4500Pa.

II. C.Mixing ratio test

II. C. 1) Determination of mixing ratios

Composite concrete ratio design of the basic requirements:

1) Easy mixing, transportation and pouring of dense construction and ease of use.

2) Meet the design strength requirements.

3) Meet the requirements of engineering durability.

(4) To meet the above three requirements under the premise of meeting the economic rationality.

Conduct the proportion test in accordance with “Composite Concrete Proportion Design Regulations” (JGJ55-2014).

(1) Determine the strength of trial mix

According to the raw material materials and P.O 42.5 cement design strength grade (<C60), the formula for determining the strength of the proportion is:

$$f_{cu.0} = f_{cu.k} + 1.625\sigma \quad (1)$$

where, $f_{cu.0}$ -Composite concrete formulated strength (MPa), $f_{cu.k}$ -Standard value of composite concrete cubic compressive strength, taking the concrete design strength value (MPa), σ -Standard deviation of concrete strength (MPa). Based on the design criteria of "Composite Concrete Proportioning Design Regulations", the coefficient in this study σ is taken as 1.625.

(2) Determine the water-cement ratio

Water-cement ratio is the main factor affecting the ease, strength and durability of concrete. In order to meet the strength and durability of the premise, choose a larger water-cement ratio is conducive to saving cement.

(3) Determine the water consumption

Water consumption per unit in concrete indicates the proportional relationship between cement paste and aggregate. After the determination of water-cement ratio, in order to save cement, the unit water consumption is taken as the smaller value under the condition of satisfying the fluidity. Composite concrete should have suitable fluidity to ensure that the concrete can flow uniformly during pouring.

(4) Determine the sand rate

Reasonable choice of sand rate plays a decisive role in the composite concrete's good or bad compatibility, and at the same time relates to the composite concrete's durability and sturdiness.

(5) Determine the amount of coarse and fine aggregates

Calculation by volumetric or mass method. The volumetric method should be calculated in units per cubic meter of concrete. For calculation by mass method, the assumed mass per cubic meter of composite concrete is taken as 2150~2350 $\mathrm{kg/m^3}$.

According to the above mix ratio test, the final mix ratio design of test specimens in this paper is shown in Table 4. Among them, P.O 42.5 cement is selected for C40 ordinary cement concrete, and RRCM material is selected as the interfacial agent for composite concrete type A and type B. Among them, RRCM composite concrete type A is suitable for small area or thin layer construction, i.e., the thickness is <20 cm, or the width of the long side is <2 m. RRCM composite concrete type B is suitable for large area or thick layer repair, i.e., the thickness is >20 cm, or the width of the short side is >2 m. The concrete repair is also suitable for large area, i.e., the thickness of the short side is >20 cm.

Table 4: List of mix ratios

Specimen class	Mix ratio				
	Cement	Water	Graded gravel		Sand stone
			5-20mm	20-35mm	
C40 Ordinary cement concrete	1	0.45	0	2.87	1.5
RRCM composite concrete Type A	1	0.40	2.81	0	1.55
RRCM composite concrete Type B	1	0.45	1.35	2.08	1.62

II. C. 2) Fabrication of test pieces

(1) The test specimen categories are shown in Table 5.

Table 5: List of specimen sizes and categories

Specimen class	Test name	Specimen size	Shape
1	Compressive strength test	200 × 200 × 200mm	Cube
2	Flexural strength test	200 × 200 × 500mm	Prismatic
3	Shrinkage test	200 × 200 × 500mm	Prismatic
4	Interface shear test of new and old concrete	200 × 200 × 500mm	Prismatic
	Sulfate resistance test		
	Freeze test		
5	Water permeability test	The upper and lower diameters are 200 mm, and the height is 150mm	Cylinder

(2) Production of specimens

According to the “universal composite concrete mechanical properties test method standard” (GB/T 50081-2002), “composite concrete long-term and durability performance test method standard” (GB/T-50082-2009) the provisions of the production of specimens. The production steps are as follows:

1) Weighing

According to the designed concrete mix ratio, weigh quantitative cement, coarse aggregate, admixture, water, admixture, etc. respectively.

2) Mixing

Utilize the laboratory concrete mixer to complete the mixing, before mixing should ensure that the mixer is clean and properly wet, put the weighed test ingredients into the mixer, turn on the mixer dry mixing for 50s, take out the raw materials. Then, add coarse and fine aggregates, admixtures, cement or RRCM materials and water into the mixer in turn and mix for 150s.

3) Molding

The well-mixed concrete is put into different specification test molds according to the test classification, and the mold loading should be completed in several times, first add the appropriate amount of concrete and then use the trowel to insert the pounding, and then continue to add the insertion pounding, until the amount of concrete loaded is slightly larger than the volume of the test mold (pre-embedded probe is required for the production of 3 types of test specimens).

4) Vibrating

The use of vibrating table for insertion pounding, will be fixed on the standard vibration table, the vibration process to maintain the stability of the position of the test mold, does not jump, until the surface of the pulp until, in order to avoid segregation and stratification, vibration time should be controlled within 50s.

5) Plastering

The specimen will be leveled and left for an appropriate period of time (before the initial setting), the concrete is smeared to remove excess concrete, and smoothed along the mouth of the mold.

II. D.Test methods

II. D. 1) Mobility test

The test refers to the method in GBT2419-2005 to measure the fluidity of each group of mortar, and the test equipment is the cementitious sand fluidity tester (referred to as jumping table).

Firstly, the tabletop, test mold, tamping rod and scraper were wiped with damp cotton cloth.

Then, the mixed mortar was loaded into the test mold in two times, the first one was poured into two-thirds of the test mold, and the pounding rod was inserted and pounded 20 times from the edge to the center.

Then pour the second layer of mortar, slightly higher than the test mold, with the pounding rod from the edge to the center of the pounding 20 times, after pounding the mortar is slightly higher than the test mold, with a scraper to scrape off the excess mortar.

Finally, remove the test mold, start the jumping table, at a frequency of once per second, jumping 20 times, after determining the width of the two perpendicular directions, and record.

II. D. 2) Mechanical Performance Test

Test with reference to GBT17671-1999 specification of the method, measure the bending strength and tensile strength of each group of specimens, including tensile strength specimens loaded at a rate of 50N/s. Bending strength for the specimen after the bending test, loaded at a rate of 2,500N/s, the area of the force is 50 × 50 mm.

II. D. 3) Percolation tests

The test refers to the method specified in the specification JGJ/T70-2009 to measure the impermeability of each group of composite concrete. The test equipment is SS-15 mortar penetrometer, the maximum working pressure is 2.5MPa, power 150W, speed 1680 rpm. Each group of 5 specimens, the specimen upper diameter of 185mm, the lower diameter of 205mm, the height of the specimen is 150mm.

Firstly, the specimens were loaded into the test molds and sealed around with glass glue to prevent water seepage from the side during the test. Then, the specimen was loaded into the mortar penetrometer and pressurized from 0.1MPa, and the constant pressure was increased by 0.1MPa every 0.5h after 1h. When there were water seepage in 3 out of 5 specimens, the water pressure data was stopped and recorded. If the water pressure is 1.5MPa when the specimen is kept for 1 hour without water seepage, the specimen will be taken out and split, and the seepage height will be measured by selecting 5 different positions at equal distances and calculating its average value.

II. D. 4) Freeze cycle test

The test refers to the test method stipulated in the Standard of Test Methods for Long-term Performance and Durability of Composite Concrete (GBT50082-2009) to determine the effects of alkali admixture, slag admixture and water-cement ratio on the freeze-thaw resistance of RRCM materials. The equipment is HC-HDK9 concrete rapid freeze-thaw tester, with temperature control accuracy of ±0.3℃, maximum operating power of 10.25KW, high temperature control of 20℃~25℃, and low temperature control of -25℃~-18℃.

The specimens were cast in 3 groups with different mixing ratios, 5 specimens in each group, and the size of the specimens was 200×200×500mm prisms. The tests were conducted with reference to the one-day temperature variation of the winter temperature in Beijing, China, with a minimum temperature of -17°C and a maximum temperature of 9°C.

First, the cast specimens were cured in a constant temperature and humidity curing box for 28 days (4 weeks) at a curing temperature of 18±3°C and a curing humidity of more than 95%.

Then, the groups of specimens were numbered and weights were recorded, and they were soaked in water for 4 days.

Finally, the soaked specimens were sequentially put into the freeze-thaw cycle box, and a batch of specimens were taken out every 20 freeze-thaw cycles, weighed, and the compressive strength and flexural strength were measured.

The formulas for each calculation are as follows:

$$\Delta m = \frac{m_0 - m_n}{m_0} \times 100\% \tag{2}$$

$$\Delta f_t = \frac{f_{t1} - f_{tn}}{f_{t1}} \times 100\% \tag{3}$$

$$\Delta f_c = \frac{f_{c1} - f_{cn}}{f_{c1}} \times 100\% \tag{4}$$

where, Δm is the rate of mass loss of the specimen, m_0 is the mass of the specimen before freeze-thaw cycles. m_n is the mass of the specimen after n freeze-thaw cycles, Δf_t is the loss rate of flexural strength of the specimen. f_{tl} is the flexural strength of the specimen before freeze-thaw cycle, f_{tn} is the flexural strength of the specimen after n freeze-thaw cycles, Δf_c is the loss rate of compressive strength of the specimen. f_{el} is the compressive strength of the specimen before freeze-thaw cycle, f_{cn} is the compressive strength of the specimen after n freeze-thaw cycles.

II. D. 5) Drying tests

The test refers to the method specified in the JTCE30-2005 specification to prepare and test the dry shrinkage performance of RRCM materials.

Firstly, the well-mixed RRCM material was poured into a 200×200×500mm steel mold in two times and placed on a vibration table for vibration.

Then, it was put into a constant temperature and humidity curing box with a curing temperature of 20°C±32°C and a relative humidity of 55±5%, and the mold was demolded after 24 hours of curing. After demolding, an electronic balance with an accuracy of 0.01g was used to determine the initial mass of each group of specimens, and a mortar specific length meter with an accuracy of 0.001mm was used to determine the initial mass and initial length of each group of specimens. Three specimens in each group were measured three times for each specimen and the average value was taken.

The mass loss rate of RRCM materials was calculated by the formula:

$$\Delta W_{ni} = \frac{W_{0i} - W_{ni}}{W_{0i}} \times 100 \tag{5}$$

where, ΔW_{mi} is the rate of loss of mass loss (%) of the i nd specimen after n days of curing, with an accuracy of 0.01. W_{oi} is the initial mass (g) of the i th specimen after demolding, with an accuracy of 0.01g. W_{mi} is the mass (g) of the i th specimen after n days of curing, with an accuracy of 0.0lg.

The mass drying shrinkage of RRCM material was calculated by the formula:

$$\varepsilon_{si} = \frac{L_{0i} - L_{ni}}{250} \times 100 \tag{6}$$

where, for ε_a is the drying shrinkage (%) of the i rd specimen after n days of conservation, with an accuracy of 0.001. L_{oi} is the initial length of the i th specimen after demolding (mm), with an accuracy of 0.001 mm. L_{ni} is the length of the i th specimen after demolding n, with an accuracy of 0.001 mm, and 250 is the effective length of the specimen (mm).

II. E. Structural modeling of durability of composite concrete

II. E. 1) Factors affecting structural durability

There are many factors affecting the structural durability of composite concrete, and this paper comprehensively analyzes the influencing factors from the aspects of environment, materials and components respectively [21].

(1) Environmental effects

Environmental impacts are mainly different parameters in different geographical areas, which can reduce the material performance. Among them, those that usually play a major role include the atmosphere, the ocean, and the chemical production environment.

Atmospheric environment is categorized into factors such as humidity, sunlight, temperature, precipitation and wind speed. Reinforced concrete materials in the atmospheric environment is prone to the phenomenon of carbonization of concrete, and in the air moisture and rainwater will lead to corrosion of reinforcing steel, that is, atmospheric corrosion.

The marine environment includes oxygen content, PH value, chlorinity, etc., which can have a greater impact on the structure of the material. The presence of sodium chloride and oxygen in the ocean, with a high content of chloride ions, will form an electrolyte solution, which promotes the rate of chloride erosion, and the erosion effect varies in different marine environments.

The chemical environment will increase the emission of carbon dioxide, chloride ions and wastewater waste, and these pollutants will accelerate the erosion rate of the steel reinforcement in the composite concrete, which directly affects the structural durability.

(2) Material impact

The transfer properties of water in the material directly affect the rate of carbonation of composite concrete, and the permeability resistance of composite concrete is described as:

$$P = HK \tag{7}$$

Where, H represents the water pressure when 10 specimens seep simultaneously. The permeability coefficient K is calculated as:

$$K = \frac{bD^2}{2TH} \tag{8}$$

where, D denotes the height of water penetration; T is the constant pressure time; and b belongs to the water absorption rate of concrete, which usually takes the value of 0.3.

In addition to water permeability, the stability of composite concrete also affects the durability of the structure. Stability is mainly manifested in deformation, cracks, etc., and these factors will aggravate the degree of destruction of the structure.

(3) Impact of components

Carbonation, a process in which the alkaline material in composite concrete reacts with carbon dioxide. Composite when the concrete absorbs water produces calcium hydroxide liquid, which is an alkaline solution with a high pH value that forms calcium carbonate inside the composite concrete, leading to carbonation of the material. The degree of carbonation is analyzed using the following equation:

$$X = \sqrt{\frac{2Dco_2 Cco_2}{Mco_2}}\sqrt{t} \tag{9}$$

where, X represents the depth of carbonation, Dco_2 represents the carbon dioxide diffusion coefficient, Cco_2 describes the concentration of carbon dioxide, Mco_2 is the rate of carbon dioxide absorption by the concrete, and t represents the duration of the carbonation process.

Rebar corrosion likewise has a very large impact on the durability of composite concrete structures, and in order to accurately analyze the durability of the structure, it is necessary to establish a rebar corrosion model, which consists of two parts: the corrosion time and the amount of corrosion. Under normal atmospheric conditions, the expression for the onset of rebar corrosion is:

$$t^{'} = \left(\frac{c - x_0}{k}\right)^2 \tag{10}$$

where, c denotes the concrete thickness, x_0 describes the carbonation residue, and k belongs to the carbonation coefficient.

The formula for calculating the amount of rebar corrosion is as follows [22]:

$$\begin{aligned} W &= k^{'} P_{RH} D_{o3} R \cdot \frac{2\left(t^{'} - \frac{x_0^2}{k^{'}}\right)}{2R + c} + \sqrt{\frac{2R + c}{c}} \\ &= \left(\sqrt{\frac{2R + c}{c}} \cdot \frac{k\sqrt{t^{'}} + x_0 - c}{\sqrt{R^2 - \left(R + c - k\sqrt{t_{cr}} - x_0\right)^2}}\right) \\ &= \frac{1}{k^{'}}\sqrt{R^2 - \left(R + c - k\sqrt{t_{cr}} - x_0\right)^2} \end{aligned} \tag{11}$$

where R represents the radius of the reinforcement, P_{RH} is a factor affecting the environment, D_{o3} represents the oxygen diffusion coefficient, $k^{'}$ is a correction factor for the degree of corrosion, and t_{cr} is the time of cracking of the reinforcement.

The above are all the factors affecting the durability of the structure, and there is a difference in the degree of influence of different aspects of the factors on the durability. In the actual analysis process, the specific conditions of each influencing factor are inputted into the building information (BIM) model, which is conducive to the improvement of the BIM database, and then produce more accurate analysis results.

II. E. 2) BIM modeling of structural durability

Based on the relationship that exists between the requirements related to the durability analysis of composite concrete structures and the different influencing factors, the designed BIM model hierarchical architecture is shown in Fig. 1 [23]. As can be seen from the figure, the BIM hierarchical architecture consists of a data acquisition layer, two processing layers and an output layer. The BIM modeling analysis can be realized by inputting all the factors affecting durability into the durability BIM model of composite concrete structures and then evaluating them by durability indexes.

The factors affecting structural durability show that the quantitative indicators for durability evaluation include carbonation depth, concrete strength, crack width, and reinforcement corrosion. Each of these indicators is rated in a different way, so a comprehensive analysis matrix must be utilized to arrive at the final durability analysis results for composite concrete structures. The detailed steps are described below:

If there is a total of m factor affecting durability, the durability of reinforced concrete structures is divided into K judgment levels, denoted as $C_1, C_2, \cdots, C_K$, and the standard value of the evaluation factor j is $a_{jK}\,(j = 1, 2, \cdots, m)$ within the K th level, the following matrix of scoring criteria is obtained:

$$a_{jK} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1K} \\ a_{21} & a_{22} & \cdots & a_{2K} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mK} \end{bmatrix} \tag{12}$$

Assuming that there is a total of P item to be adjudicated and that the true value of evaluation factor j in the first item is $x_{ij}\,(i = 1, 2, \cdots, P)$, the measurement matrix is as follows:

$$x_{ij}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & & \vdots \\ z_{P1} & x_{m2} & \cdots & x_{Pm} \end{bmatrix} \tag{13}$$

Assuming that the evaluation factor j in item i to be tested has measure μ_{ijK} of attribute G_K, the combined rating matrix is as follows:

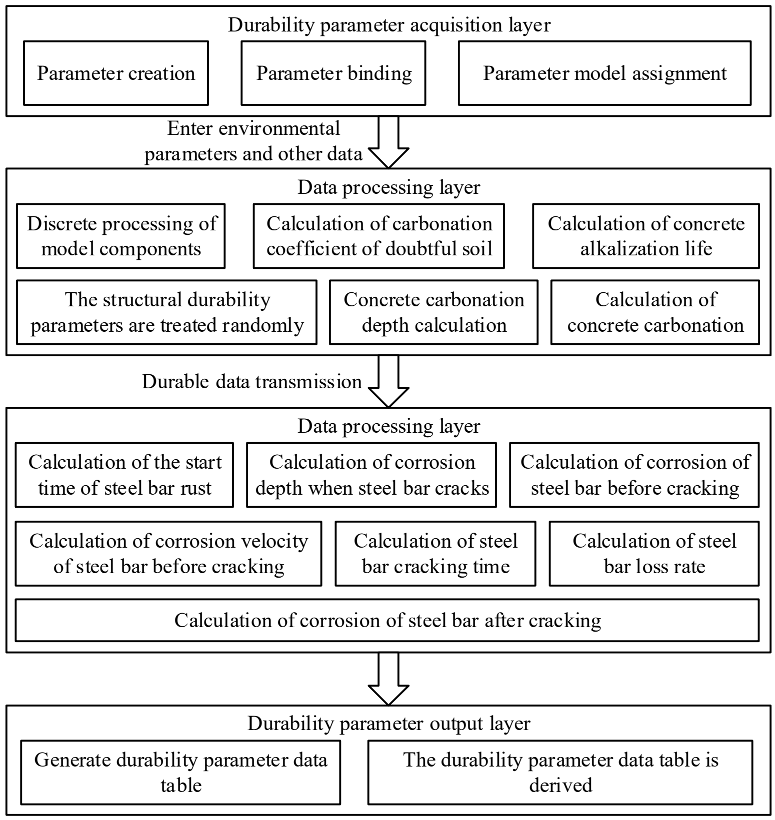


Figure 1: Hierarchical architecture diagram of BIM model

$$\mu_{ijK}=\begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1K} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{12K} \\ \vdots & \vdots & & \vdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imK} \end{bmatrix} \tag{14}$$

Using the above established structural durability quantitative comprehensive determination matrix, the durability analysis results of composite concrete are obtained, and the quantitative grades are shown in Table 6. At this point, the complete composite concrete structure durability BIM quantitative analysis model construction is completed.

Table 6: Quantitative classification of durability of composite concrete structures

Durability level	Score
First level	≥4.5
Second level	<4.5, ≥4.0
Three level	<4.0, ≥3.0
Four level	<3.0, ≥2.0
Fifth level	< 2.0

III. Test results and analysis

III. A. Analysis of Mechanical Properties of RRCM Composite Concrete

III. A. 1) Tensile strength test results

With the help of finite element post-processing after the completion of the dry shrinkage test, the axial compression damage damage destruction process of RRCM composite concrete specimens under different loading history, as well as the distribution and development of stress and deformation in different components and parts can be visually studied, which further reveals the synergistic work, stress performance and destruction mechanism of RRCM materials applied to composite concrete. Figure 2 shows the load-displacement curves of the whole process of axial compression of RRCM composite concrete type A (RRCM material mixing ratio of 1.5%) cylindrical specimen, and six representative characteristic points A~F are selected to analyze the compression damage of constituent parts and the stress distribution law and so on. Among them, point F is the load capacity limit, the specific load is 4105kN, and the degree of deformation is 12.5mm.

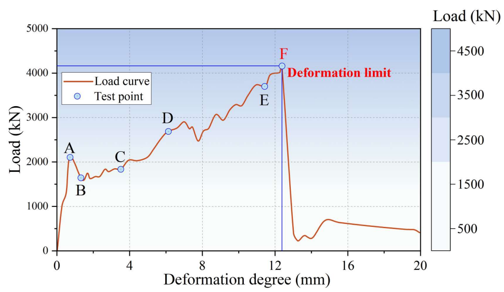


Figure 2: Load-displacement curve of RRCM composite concrete A-type axial column

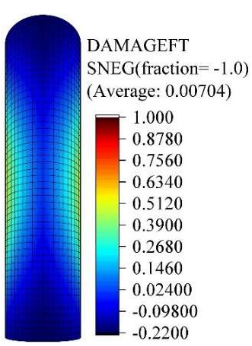
The damage factor (DAMAGEFT, d) characterizes the damage destruction degree of the specimen, and the larger value of d represents the larger damage. Figure 3 shows the damage and stress cloud diagrams of RRCM composite concrete characteristic points A~F, respectively, at different loading stages:

(1) Point A

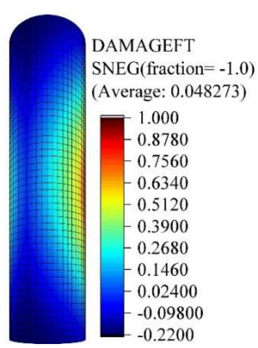
RRCM composite concrete cylindrical specimen first appeared in the middle of a certain degree of compression damage, and the damage factor is maximum about 0.40, the overall damage factor is 0.00704. compressive stress is maximum about 35.2MPa, it is seen that the specimen compressive stress reaches its axial compressive strength, take the lead in the expansion and deformation of the microcracks generated by the radial stress is transferred to the RRCM, at this time, the tensile stress in the RRCM material is about 125.4MPa, indicating that its restraining effect is still small.

(2) Point B

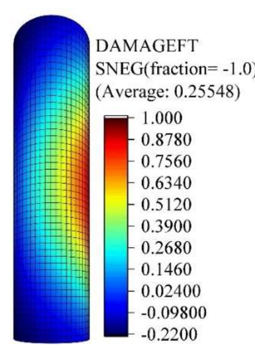
Specimen compression damage to the middle of the cylinder expansion, compression damage factor maximum of about 0.55, the overall damage factor of 0.048273. specimen bearing capacity of a small steep decline in the internal force redistribution, RRCM material compressive stress of about 67.2MPa, radial stress is further transferred to the RRCM material, at this time, the tensile stress of the RRCM is about 552.4MPa, indicating that the ring constraint effect began to enhance.



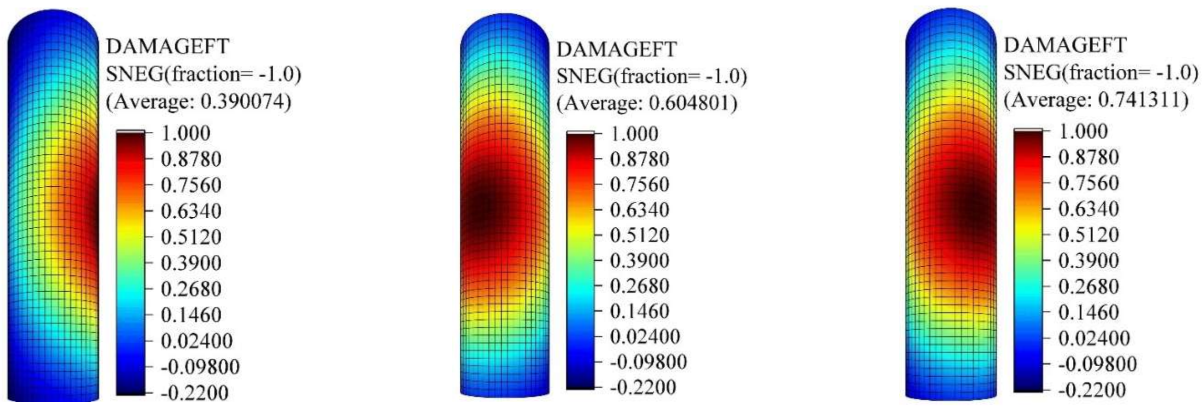
(a) Point A



(b) Point B



(c) Point C



(d) Point D (e) Point E (f) Point F

Figure 3: Failure process of specimen under axial compression

(3) Point C

The range of compressive damage extends upward and downward, the maximum compressive damage factor is about 0.76, and the overall damage factor is 0.25548. The specimen carries a compressive stress of about 87.2 MPa, the microcracks of the internal structure of the RRCM composite concrete increase gradually, and the volume continues to expand transversely, and the tensile stress supplied by the RRCM material is about 955.8 MPa.

(4) Point D

The range of compressive damage gradually extends to the whole height, and the compressive damage in the middle of the specimen is more serious than the two ends, and the overall damage factor comes to 0.390074. Under the restraining effect of RRCM material, the compressive stress of the specimen increases steadily to about 105.1MPa, and the tensile stress provided by the RRCM material is about 1,258.0MPa.

(5) Point E

Before the damage of the corresponding specimen, the compressive stress of the three-way complex stress state in the middle of the height is as high as 179.2MPa under the effective restraint of RRCM material, which is 192.4% higher than that of C40 ordinary concrete without RRCM material restraint, and the strength of RRCM material is fully utilized.The tensile stress provided by the RRCM material grows faster, which is 2,482.4MPa.The design of the composite concrete with the application of RRCM material is verified, which is the best solution for the design of the composite concrete. It is verified that RRCM material is applied to the design of composite concrete, and its damage resistance is significantly improved. The joint restraining effect of RRCM material and cement, the compression expansion deformation and shear brittle damage is greatly delayed and improved.

(6) Point F

During the loading process from point B to point F, the restraining effect of RRCM material is increasing, the compressive stress and transverse volume expansion are increasing, and the circumferential tensile stress of RRCM material is increasing. Close to point F, the middle of the specimen extrusion cracking is serious, the expansion deformation increases rapidly, and the RRCM composite concrete type A designed in this paper, reaches the ultimate tensile strength and breaks (the ultimate strength is 4105kN), and the specimen is finally destroyed.

III. A. 2) Flexural strength test results

RRCM composite concrete Type B flexural and tensile specimens were prepared according to the previously described method and mix ratio, and their flexural and tensile strengths were tested for 7d, 14d, 21d, and 28d beam specimens, and the results of the tests are shown in Table 7, and in Fig. 4. The RRCM Type B (10-25) specimen, for example, refers to the RRCM composite concrete Type B specimen, where 10 represents the aggregate particle size of about 10 mm and 25 represents the mixing amount of RRCM material of 25 kg/m^3 . The experimental results show that the effect of RRCM material on the flexural strength of composite concrete is similar to its tensile strength. The 28d flexural strength of RRCM Type B specimens with 10 mesh and 30 mesh was increased by 30.84%, 25.29%, 18.97%, 2.11% and 31.03%, 25.67%, 20.31%, 12.45% respectively compared to that of C40 plain concrete when the admixture was 25 kg/m^3 , 50 kg/m^3 , 75 kg/m^3 , and 100 kg/m^3 respectively. When using the same mesh size of RRCM material as an interfacial agent to replace sand and gravel, the more the replacement i.e., the more the rubberized aggregate mix, the weaker the effect of composite concrete flexural strength enhancement.

Table 7: Results of flexural tensile strength test

Specimen number	Flexural tensile strength (MPa)			
	7d	14d	21d	28d
C40 Ordinary cement concrete	2.31	3.99	4.62	5.22
RRCM Type B (10-25)	3.16	4.73	5.54	6.83
RRCM Type B (10-50)	2.84	4.52	5.36	6.54
RRCM Type B (10-75)	2.36	4.36	5.10	6.21
RRCM Type B (10-100)	2.15	3.76	4.97	5.33
RRCM Type B (30-25)	3.25	4.79	5.56	6.84
RRCM Type B (30-50)	3.06	4.55	5.45	6.56
RRCM Type B (30-75)	2.43	4.26	5.32	6.28
RRCM Type B (30-100)	2.18	4.15	5.16	5.87
RRCM Type B (50-25)	3.17	4.66	5.49	6.80
RRCM Type B (50-50)	2.83	4.41	5.26	6.16
RRCM Type B (50-75)	2.21	3.84	4.71	6.04
RRCM Type B (50-100)	2.06	3.71	4.66	5.22

The minimum strength of 28d is 5.22MPa, according to the relevant standards, when the flexural strength is more than 5MPa, it can meet the requirements of expressway, trunk road and heavy traffic loading area.After replacing sand and gravel, the RRCM material acts as a spring in the composite concrete. When external load, the deformation of coarse aggregate and the deformation of the surrounding concrete to produce the difference between the rubber aggregate and the cementitious material slurry easier to separate, so the concrete flexural tensile strength compared to ordinary concrete has increased, the more the mixing, the weaker the role. The optimal amount of RRCM material should be controlled within 25%. Moreover, among the three particle sizes, 30mm RRCM composite concrete has the highest flexural strength and 50mm RRCM composite concrete has the lowest flexural tensile strength. This is because the 30mm RRCM material has a micro-grading effect, which can fill some of the pores in the concrete and increase the densification, which compensates for the loss of strength caused by the material to a certain extent. In addition, due to the 50mm RRCM particles are finer, mixed into the concrete and the cement combined with the weak points generated by the increase in the bond effect is weakened, resulting in its ability to withstand less force, therefore causing the most significant decrease in its strength.

III. B. Durability analysis of RRCM composite concrete

In this chapter, concrete carbonation test and reinforcement corrosion test will be conducted to realize the assessment method of durability of composite concrete structures based on BIM technology, and to illustrate the accuracy and adaptability of the durability structural modeling technique even further.

III. B. 1) Analysis of carbonation tests

Referring to GB/T50082-2009 specification 11.0.5, the carbonization depth of 3d, 7d, 14d and 28d should be measured, but due to the thin wall of this test box girder and the small test sample size, the carbonization time is too short, which will make the carbonization depth of the error is larger. The carbonization effect of each parameter is shown in Figure 4. Carbonation test involves four environmental factors, due to the experimental conditions, the humidity and temperature factors will be set to constant light, respectively, 40% and 20 ° C. Reaction time and concentration of the two environmental factors as a control variable, which the reaction time were 3d, 7d, 14d and 28d, respectively, the concentration of 5% and 10% of the two environments. Eight pieces of RRCM composite concrete specimens were numbered as #1-#8, corresponding to eight working conditions, and were placed into the CCB-70F concrete carbonation test chamber according to the requirements, and the rapid carbonation test was carried out in accordance with the durability parameters proposed in subsection 2.5.

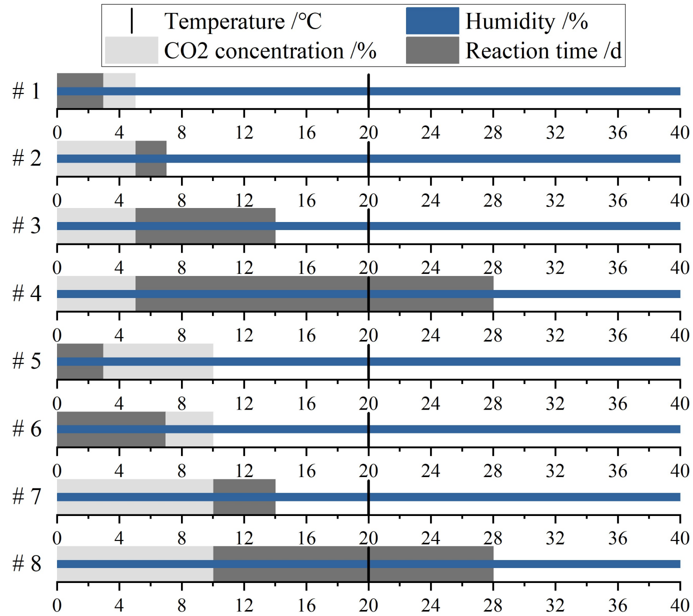


Figure 4: Carbonization influence parameters of various environmental conditions

It is known that the pH of RRCM composite concrete in the uncarbonated zone is 11 to 12. After carbonation, its pH drops to 7 (neutral). Using the phenolphthalein reagent's property of turning red in the presence of alkali, the measurement of carbonation depth was carried out Spraying a phenolphthalein one-alcohol solution on the concrete cuts allowed the demarcation line to be determined and the depth of carbonation of the concrete to be measured. The choice of measurement points only consider one-dimensional carbonation, both internal and external midpoints were selected for measurement.

When #1-#8 specimens respectively reached the standard carbonation time, take out the specimens for cutting, the cutting position for 1/2 span and 1/4 span, after the completion of cutting in the cut surface spraying 1% phenolphthalein an alcohol solution, the color of the concrete reinforcement cut surface using the accuracy of 0.5mm vernier calipers to measure the depth of carbonation.

The carbonation calculation steps of RRCM composite concrete based on BIM model are as follows:

(1) Establishment of BIM durability model database

First, a new RRCM composite concrete model is created in Revit according to the size of the test box girder model and imported into the project to complete the BIM model.

Next, add durability parameters to the BIM model, and only three parameters of concrete compressive strength, carbonation coefficient and carbonation depth need to be added for this test. Among them, the flexural strength value of concrete (RRCM Type B (10-25)) was measured as 3.16, 4.73, 5.54, and 6.83 MPa for 3d, 7d, 14d, and 28d, respectively, in the previous test.

This value is added to the model to complete the establishment of the durability model database for carbonation depth calculation.

(2) Environment, selection of coefficient parameters and calculation of carbonation depth

Calculation of carbonation depth needs to calculate the carbonation coefficient, the parameters to be determined are carbon dioxide concentration C_{CO_2} , corner correction factor k_j , working stress influence factor k_s , casting surface correction factor k_p , ambient temperature T and ambient relative humidity RH. respectively, take the coefficients k_j =1, k_s =1, k_p =1, the 8 kinds of specimens were in accordance with the above conditions of the value of the environmental parameters, and one by one to carry out calculations, and the results of the calculations are shown in Fig. 5. The BIM model calculates that when the carbonization time is 28d, the carbonization depth reaches 9.593mm and 12.522mm under the CO_2 concentration of 5% and 10%, respectively.

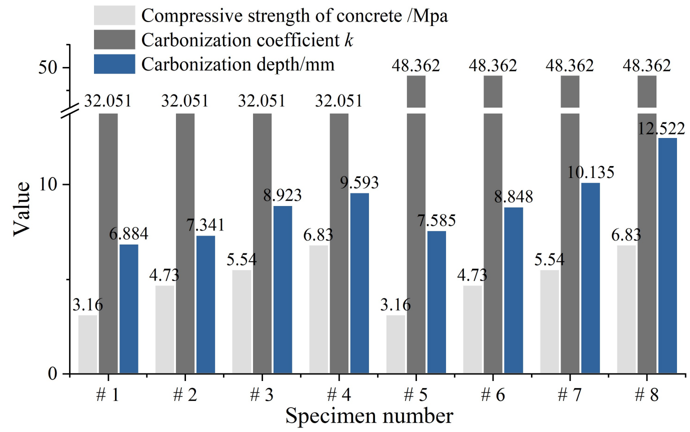


Figure 5: Details of the calculation results of carbonization depth

The actual carbonation depth results of 8 specimens measured by X-ray fluorescence spectrometer, Fourier transform infrared spectrometer, and electron microscope and other precision equipment are compared with the calculated results based on BIM modeling technology, and the results are shown in Figure 6. By comparing the test results of carbonation depth and the calculation results based on BIM technology, it is found that the largest difference between the two results is for concrete specimen #4, with a difference of 0.731mm, and the largest absolute error percentage is for specimen #1, with a difference of 7.27%. The absolute errors for the 8 kinds of specimens are all within 10%. So it is feasible to calculate the carbonation of composite concrete structure based on BIM modeling technology and this method can be used for the evaluation of concrete carbonation.

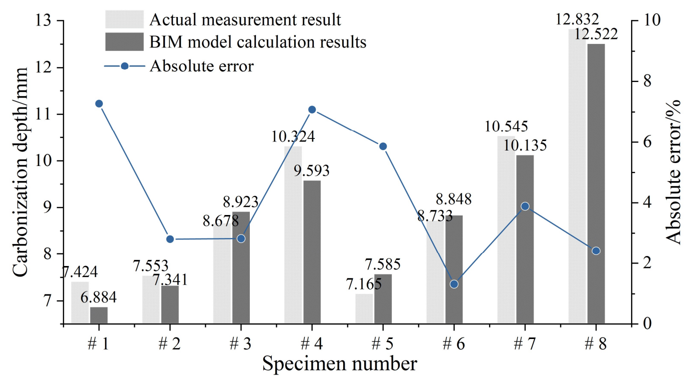


Figure 6: Comparison of carbonization depth results (unit: mm)

III. B. 2) Rebar corrosion test analysis

On the basis of the carbonation test conditions, the new RRCM composite concrete reinforcement corrosion calculation project, the new cross-section size of 100 × 100 × 100mm square model, make the sectional view, set the thickness of the protective layer of 12mm, in the component model cross-section of the side of the location of the middle position of the arrangement of φ 5 (rebar diameter = 5mm) of the rebar, to complete the construction of the BIM model. Next, the durability parameters are added to the BIM model, and the parameters to be added in this test are compressive strength of concrete, carbonation coefficient, carbonation depth, time of the beginning of the corrosion of steel bars, time of the corrosion and cracking of steel bars, amount of the corrosion of steel bars before the corrosion and cracking of steel bars, amount of the corrosion of steel bars before the corrosion and cracking of steel bars, and the rate of the corrosion of steel bars. Among them, the flexural strength values of RRCM composite concrete (RRCM Type B (10-25)) were measured to be 3.16, 4.73, 5.54, and 6.83 MPa for 3d, 7d, 14d, and 28d, respectively, which were added to the model to complete the establishment of the database of the durability model for the calculation of reinforcement corrosion.

Calculation of reinforcement corrosion requires carbonization calculations to be carried out first, and the parameters to be determined are carbon dioxide concentration C_{CO_2}, corner correction factor k_j, working stress influence factor k_s, casting surface correction factor k_p, ambient temperature T and ambient relative humidity RH. The coefficients k_j =1, k_s =1, k_p =1, and PH = 7.5, respectively, were taken for carbonization, the results of which were transferred to the reinforcement, and the coefficients for the calculation of corrosion of the reinforcement were determined. The environmental impact factor PRH is the ratio of the number of days with ambient relative humidity greater than 60% to the total number of days of rebar corrosion. In view of the rebar corrosion test is 7d in the conservation box, humidity is greater than 60%, 2d in the outdoor, humidity is less than 60%, take PRH = 7.8, rebar location correction factor $k_{cr} = 1$, rebar location impact factor k_{crs} = 1.35, small environmental correction factor take k_e = 2, the rebar corrosion calculations, the results of the calculation are shown in Table 8. It can be seen that eight specimens in eight environmental conditions of the time of the beginning of the corrosion of the rebar, the amount of corrosion of the rebar before rusting and cracking, and the rate of loss of rebar have achieved the same value, which is 0.015528 days, 0.000091 and 0.0351%, respectively.

Table 8: Calculation results of steel corrosion rate based on BIM durability model

Test piece	Protective layer	Bar diameter	Time of onset of rust	Corrosion of steel bar before cracking	Loss rate of rebar
#1	15mm	5mm	0.015528d	0.000091	0.0351%
#2	15mm	5mm	0.015528d	0.000091	0.0351%
#3	15mm	5mm	0.015528d	0.000091	0.0351%
#4	15mm	5mm	0.015528d	0.000091	0.0351%
#5	15mm	5mm	0.015528d	0.000091	0.0351%
#6	15mm	5mm	0.015528d	0.000091	0.0351%
#7	15mm	5mm	0.015528d	0.000091	0.0351%
#8	15mm	5mm	0.015528d	0.000091	0.0351%

After the calculation was completed, the test results were compared and analyzed with the test results, as shown in Table 9. By comparing the test results of rebar corrosion rate with the calculation results based on BIM technology, it is found that the maximum error of BIM technology results over the test results is 28.13%. The difference in their results is large, and the reason for this is analyzed from the perspective of BIM technology, from the calculation of carbonation to the calculation of steel corrosion, the selection of the coefficients will cause the accumulation of errors, and analyzed from the perspective of the test, due to a part of the uncertainty of the test, such as the densification of the RRCM composite concrete and other reasons will also cause the error. Therefore, the calculation results of steel corrosion calculation based on BIM technology can be used for practical engineering durability calculation for reference.

Table 9: Comparison of results of steel corrosion rate

Test piece	Test result			BIM results	Actual error/%	Absolute error/%
	The initial weight of the steel bar/g	Weight of corroded steel bar /g	Corrosion rate /%	Corrosion rate /%		
#1	80	79.7080	0.3650	0.3562	0.0088	2.41
#2	80	79.7529	0.3089	0.3562	-0.0473	15.31
#3	80	79.7776	0.2780	0.3562	-0.0782	28.13
#4	80	79.7028	0.3716	0.3562	0.0154	4.14
#5	80	79.7632	0.2960	0.3562	-0.0602	20.34
#6	80	79.7665	0.2919	0.3562	-0.0643	22.03
#7	80	79.7733	0.2834	0.3562	-0.0728	25.69
#8	80	79.7408	0.3240	0.3562	-0.0322	9.94

IV. Conclusion

The new RRCM composite concrete is prepared in the form of RRCM material and cement compounding, and different mixing ratio schemes are designed, on the basis of which the mechanical and durability properties are investigated. Combined with BIM modeling and analysis method for structural durability assessment, and establish the structural durability model database of RRCM composite concrete, the following conclusions are drawn:

(1) The mechanical properties of RRCM composite concrete type A and B are better than C40 ordinary cement concrete. Among them, the ultimate tensile strength of Type A was 4105kN when the specimen was finally destroyed. Type B was able to increase the flexural strength by a maximum of 30.84% at 28d compared to C40 plain concrete.

Meanwhile, 25% of RRCM can be identified as the optimum admixture, which can significantly improve the early shrinkage performance of RRCM composite concrete.

(2) The structural durability of RRCM composite concrete is excellent, which is better than that of C40 ordinary concrete, and can effectively guarantee the long-term use of concrete structures.

(3) BIM modeling technology in the structural durability of composite concrete, carbonation depth assessment achieved a maximum absolute error of 7.27%, and reinforcement corrosion rate assessment achieved a maximum error of 28.13%. The evaluation results can be used in real projects to provide reference for the structural durability calculation of composite concrete.

Results durability analysis is a very complex process, with the diversification of building structures, there are still some places to improve this paper, and should be more comprehensive in analyzing the influencing factors. For example, analyzing the chloride ion erosion process, etc., more factors are introduced into the BIM model in order to further improve the accuracy and scientificity of the assessment results.

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