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Preface

Concrete is developing toward high performance, high toughness, and high durability to meet the requirements of engineering. However, autogenous shrinkage usually occurs in concrete mainly attributed to the reduction of water content in concrete caused by cement hydration, and this phenomenon is aggravated by the low water-to-binder ratio. Additionally, the cement hydration heat contributes to the temperature rise in concrete, the evolution of temperature in mass concrete is similar to the adiabatic condition, and the temperature drop in concrete may increase the thermal shrinkage. Once the shrinkage of concrete is restrained, tensile stress develops with the increasing elastic modulus and may exceed the tensile strength of concrete, resulting in the occurrence of cracks. Besides, from the perspective of strain-based criterion, the crack may occur if the restrained strain exceeds the tensile strain capacity of concrete. The cracking of concrete adversely weakens the integrity of the structure, which may impair the waterproofing properties and reduce the durability of concrete, as well as bring some security problems for structures. Therefore, reducing the shrinkage is necessary for decreasing the cracking failure potential of concrete, which is essential to ensure the safety and durability of concrete structures. Many methods are used to control the early-age cracking of concrete, including different kinds of fibers, supplementary cementitious materials, chemical admixtures, internal curing materials, etc. However, systematics investigations on the cracking control of concrete are lacking.

This monograph presents a summary of the key theoretical and experimental findings from the decades of investigations conducted at the College of Civil and Transportation Engineering, Hohai University, Nanjing City, China, with a specific focus on the assessment and control of cracking of early-age concrete in the recent decades. In this monograph, the techniques of crack control of modern concrete at early age are further developed through experimental and theoretical research, such as mitigating the drop in internal relative humidity, controlling the change of temperature, decreasing the shrinkage, and increasing the tensile strength. It reveals the mechanism of early-age cracking control of modern concrete with mineral admixtures, fibers, shrinkage reducing admixtures, nanomaterials, temperature rise inhibitors, and internal curing materials under circumferential or uniaxial restrained conditions. It also reports innovative findings and establishes prediction models on early-age internal relative humidity, autogenous shrinkage, and tensile creep of modern concrete considering water-to-binder ratio, curing temperature, etc. The author hopes that it will be useful to professionals, practitioners, as well as graduate or undergraduate students, and that it will serve as a reference for them.

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Dr. Ci Liu prepared the draft for Chaps. 1, 2, and 13. Dr. Jiacheng Kang prepared the draft for Chaps. 1, 2, 6, 8, and 14. Dr. Chuyuan Wen prepared the draft for Chaps. 1, 2, 7, 9, 16, and 17. Dr. Zhizhuo Feng prepared the draft for Chaps. 1, 2, 10, 11, and 12. Dr. Haoze Shao prepared the draft for Chaps. 1, 2, 3, 5, and 15. Dr. Quan Huang prepared the draft for Chaps. 1, 2, and 4. Teams members in the author's research group made a great contribution to the preparation of this monograph, including Mr. Haokang Wang, Mr. Zhihao Wang, Mr. Yifan Wei, Mr. Songlin Bai, Mr. Hanbin Xu, Mr. Jingwang Yao, Ms. Yueyao Luo. Students in the author's research group contributed a great deal to the research work and completion of this monograph, including Mr. Yin Chen, Mr. Jiaxin Shen, Mr. Xiaojian Tang, Mr. Yongqiang Shen, Mr. Tao Wang, Ms. Panpan Yao, Mr. Xiaoguang Zhao, Mr. Shuaishuai Zhu, Mr. Huafeng Shi, Mr. Xiang Shi, Mr. Lei Sun, Mr. Yuhua Wu, Mr. Jinliang Jiang, Mr. Kaiqi Liu, Mr. Baizhong Zhou, Mr. Xingzuo Liu, Ms. Wenting Wang, Mr. Xuan Zeng, Mr. Xusheng Chen, Mr. Miao Wang, Ms. Shiqian Xu, Mr. Yang Jiao, Ms. Hui Tang, Ms. Zhilan Xu, Mr. Liukun Zhou, Ms. Tingting Zhang, Mr. Jiacheng Kang, Mr. Ci Liu, Mr. Zhizhuo Feng, Ms. Chuyuan Wen, and Mr. Haoze Shao. Their hard work, dedication, and intelligence have contributed considerably to the work presented in this monograph.

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Contents

Abbreviations

CTE	Coefficient of thermal expansion
FA	Fly ash
GGBFS	Ground granulated blast furnace slag
HPC	High performance concrete
HSC	High strength concrete
IRH	Internal relative humidity
LWAs	Lightweight aggregates
PP fiber	Polypropylene fiber
PVA fiber	Polyvinyl alcohol fiber
RH	Relative humidity
SAPs	Superabsorbent polymers
SRA	Shrinkage reducing admixture
TRI	Temperature rise inhibitor
TSTM	Temperature Stress Test Machine
w/b ratio	Water-to-binder ratio
w/c ratio	Water-to-cement ratio
w_{ic}/c ratio	Internal curing water-to-cement ratio

Chapter 1
Introduction

1.1 Early-age Cracking of Modern Concrete

1.1.1 Significance of Early-age Cracking

Concrete is one of the most widely used human-made materials due to its versatility, durability, and relatively low cost, with an estimated 14 billion cubic meters produced annually worldwide [1]. Concrete is utilized in a wide range of applications including building structures, bridges, dams, roads, tunnels, substructures, high-rise buildings, and nuclear reactors [2]. Early-age cracking in concrete structures is a significant concern for engineers because it can lead to structural failure and reduce service life of concrete structures. Concrete is a material that is prone to cracking due to various factors such as shrinkage, thermal expansion, and loading. These cracks can occur during the curing process of the concrete when the material is still in its most vulnerable state. Early-age cracking is particularly important to be addressed as it can occur in the first few days after the concrete is placed and can be caused by several factors, including temperature changes, humidity, and the type of aggregate used in the mixture.

One of the most significant problems associated with early-age cracking is the potential for structural failure [3]. Cracks in concrete can weaken the structure and make it more susceptible to failure under load. This is especially concerning in critical structures such as bridges and high-rise buildings, where a failure could have catastrophic consequences. In addition to structural failure, early-age cracking can also lead to a reduction in the service life of the concrete structure. Cracks in concrete can allow water with chemical agents and gases to infiltrate to penetrate the structure, which can lead to corrosion of the reinforcing steel and other structural components. If the cracks in concrete continue to develop, it may affect the bearing capacity of the structure and accelerate fatigue failure [4, 5]. Early-age cracking can also have a significant impact on the aesthetics of the concrete structure. Visible cracks can detract from the appearance of the structure and can lower its value. This is

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particularly concerning in architectural concrete structures where the appearance of the concrete is an important consideration. Early-age cracking in concrete structures can lead to significant maintenance costs. Cracks can lead to corrosion of reinforcing steel and other structural components. This can cause the concrete to deteriorate over time and require costly repairs or even replacement. In addition, visible cracks can detract from the appearance of the structure and lower its value, which can lead to additional costs for repairs or replacement. Additionally, when the development of cracks affects the functionality and durability of the structure, certain materials need to be used to block the cracks promptly, and when the cracks reduce the bearing capacity of the structure, strengthening the structure is necessary. These steps also require additional costs and resources.

1.2 Causes of Early-age Cracking

Cracking is a common problem in concrete structures in real-life service conditions. Early-age cracking occurs in concrete structures due to the low tensile strength, high-temperature difference, and high shrinkage development during the hardening of concrete under restrained conditions. The main causes of early-age cracking can be grouped as follows.

Tensile strength is a significant characteristic of cementitious materials at early age. The tensile strength of early-age concrete is relatively low although it increases with age [6]. The values of mean tensile strength at 3 d are around 60% of the values at 28 d following data of EN1992-1-1 [3]. Internal micro-cracks are inherently present in concrete and their low tensile strength is attributable to the propagation of these micro-cracks, ultimately contributing to brittle fracturing [7]. Concrete, as a brittle material, is considered to have low post-cracking strength and ductility. In plain concrete, cracks occur when the primary tensile stresses of plain concrete exceed the tensile strength of concrete [7]. Consequently, improving the brittleness and reducing the possible weaknesses of concrete is expected to lead to better performance in various applications.

Early-age thermal cracking is associated with the release of the hydration heat from the binder [3]. The differential expansion within an element during heating causes internal restraint or external restraint, which also causes early-age thermal cracking. Early-age thermal cracking occurs within a few days in thinner sections, but it may take longer to develop in thicker sections which cool more slowly [8]. Thermal strains driven by high-temperature gradients occur between the interior and surface of structural elements since concrete has poor thermal conductivity [3]. The partial and fully restrained movement from the cooling or other temperature changes induces tensile stress in concrete. If such strains or stresses reach a certain limit, undesirable cracks can occur [9].

Shrinkage of concrete cannot be avoided, and it will occur due to the volume reduction resulting from the hydration of cement and water, which consumes less space than the initial products [10, 11]. Additional shrinkage can also be caused by drying. High shrinkage is one of the major factors contributing to the cracking of concrete structures [12]. To assess the cracking resistance associated with shrinkage, it is critical to view all aspects of shrinkage: in different stages and driven by different mechanisms. Shrinkage of concrete takes place in two distinct stages: early and later ages [11]. Within each of these two stages of shrinkage, there are also different types of linear change which can be physically measured on a specimen, mainly drying and autogenous. In addition to drying and autogenous shrinkage, the concrete is also subjected to volume reductions due to thermal changes and carbonation reactions [13]. Early-age restrained shrinkage is a concern because concrete has the lowest strain capacity and is most sensitive to internal stresses [7, 11]. Besides, restrained conditions such as circumferential and uniaxial restrained conditions will also affect the cracking behavior of concrete. If there is no restraint, concrete will not crack. The different restrained conditions will cause different stress distributions, thereby causing different cracking behavior. Deleterious substances introduced into the concrete along the cracks exhibit adverse effects on the performance of concrete, therefore shortening the lifetime of the structure [14].

1.3 Measures for Controlling Early-age Cracking of Concrete

1.3.1 Mitigating the Drop in Internal Relative Humidity

The shrinkage-induced cracking of concrete is associated with the drop in internal relative humidity (IRH) caused by moisture loss [15]. The shrinkage deformation increases proportionally with the drop in IRH. The moisture loss of concrete is related to ambient drying and cement hydration. Drying shrinkage occurs as the reason that the moisture in concrete diffuses into the outside ambient when the ambient humidity is lower than IRH in concrete. Cement hydration consumes water and causes the occurrence of self-desiccation, which will contribute to the development of autogenous shrinkage [16, 17]. Curing agents, plastic sheeting, mono-molecular films, water fogging, or wind breaks in conjunction with properly designed concrete mixtures are used to prevent the evaporation of moisture in the concrete [18], which can not only prevent the plastic shrinkage cracking but also increase the cracking resistance under the influence of autogenous shrinkage or drying shrinkage. In recent years, studies have illustrated that the application of internal curing materials such as superabsorbent polymers (SAPs), pre-wetted lightweight aggregates (LWAs), and rice husk ash [19] can effectively mitigate the drop in IRH, and the efficiency of internal curing is higher than that of external water curing [20]. In the preparation of the concrete mixture, the water can be absorbed by internal curing materials and then released gradually during the process of moisture diffusion and cementitious materials hydration [20].

1.3.2 Controlling the Change of Temperature

Temperature differentials can generate internal restraint in thick sections. The tensile strain at the surface may be caused by restrained contraction but may also be the result of the expansion of the core of the section. When volume change is limited by external restraint, compressive stresses induced during the heating phase are relieved by creep and tensile stresses are induced during the cooling phase from the time of the peak temperature. For a given magnitude of restrained thermal strain, the compressive stress generated during heating is lower than the tensile stress generated during cooling, resulting in a residual tensile stress at the end of the heat cycle. If the residual tensile stresses are excessive, cracking occurs [21].

Ground granulated blast furnace slag (GGBFS) and fly ash (FA) are general by-products that have been utilized as mineral admixtures to produce high performance concrete (HPC) [22]. The temperature rises of HPC decreased with the increasing of GGBFS content, and GGBFS has been used to control the change of temperature. The hydration heat caused by C_3S and C_3A decreases when the cement content decreases [23]. The addition of GGBFS can slow down the speed of the hydration reaction, which decreases the heat caused by cement hydration indirectly.

Temperature rise inhibitor (TRI) is a polymeric admixture prepared by acid hydrolysis of corn starch to reduce the hydration heat release of concrete [24, 25]. The addition of TRI would depress the main hydration peak to have a lower maximum heat flow and less heat release during the first few days, which may be beneficial in mitigating the delayed ettringite formation risk. The difference in the heat flow is mainly caused by changing the calcium silicate hydrates nucleation. Besides, the addition of TRI would mainly affect the calcium silicate hydrates precipitation and partly change the surface environment of the cement particle [26].

1.3.3 Decreasing the Early-age Shrinkage

Shrinkage of concrete can occur at early ages and later ages. The first stage (within the first 24 h) corresponds to a duration in which concrete is setting and starting to harden, while the second stage corresponds to the age beyond 24 h [27]. Shrinkage at both stages mainly includes autogenous shrinkage, drying shrinkage, and thermal shrinkage which have overlapping results but with different mechanisms [27]. The cracking resistance of concrete can be improved by decreasing the early-age shrinkage [28], some common measures are summarized as follows.

Different kinds of fibers can be incorporated into concrete to decrease early-age shrinkage, which also prevents the propagation of micro-cracks in concrete. Fibers such as steel fiber (hooked-end fiber, straight fiber, undulated fiber, etc.), polyvinyl alcohol (PVA) fiber, polypropylene (PP) fiber, and cellulose fiber have been used to decrease the early-age shrinkage of concrete [29]. The addition of steel fibers markedly suppressed the shrinkage of concrete [30, 31]. Among fibers other than steel, PP fibers are more widely used in HPC [32]. Extensive research on the effects of PP fibers on plastic shrinkage and early-age cracking is available in [33]. Results in [34] report that the effect of 1% PP fiber is remarkable in the reduction of autogenous shrinkage. Results in [35] report that the autogenous shrinkage decreases, while the temperature drop, cracking age, cracking stress, and cracking stress/axial tensile strength of high strength concrete (HSC) increase with increasing volume fraction of PVA fiber. Results in [36] report that the addition of 1% cellulose fiber significantly inhibits the cracks caused by autogenous shrinkage due to the internal solidification of the matrix.

The hydration of expansive agents such as the type of sulphoaluminate [37–39], CaO [40–42], or MgO [43, 44] can lead to expansion, which is used to compensate for autogenous shrinkage or thermal shrinkage of concrete [45]. The expansion of CaO-based expansive agent usually occurs at the early stage due to the fast hydration, and therefore, the thermal shrinkage of concrete cannot be well compensated at a later stage [46]. The MgO-based expansive agent has drawn great attention attributed to its good expansive behavior, such as the relatively low water requirement, chemically stable hydration products, and the designable expansion properties [47, 48]. The autogenous shrinkage at early hydration stage and thermal shrinkage of concrete at a later age can be well compensated with the addition of CaO-based expansive agent and MgO-based expansive agent, respectively [49]. Therefore, the expansion of MgO-based expansive agents composed of different reactivities and other types of expansive agents can well compensate for the shrinkage of concrete at early hydration stage and later age [50]. Results in [51] indicate that MgO expansive agents were more efficient in cement-based materials with a low water-to-binder ratio.

Shrinkage reducing admixture (SRA) significantly reduces the shrinkage of HSC at early age by reducing the surface tension of pore solution in the cement [52]. The effects of SRA on autogenous shrinkage are reported in [53, 54]. Results in [55, 56] indicate the effect of SRA (0, 1% and 2%) on autogenous shrinkage of fiber reinforced HPC in free and restrained states and reveal that the content of SRA had a negative correlation with the autogenous shrinkage. Results in [57] report that for an SRA content of 2%, the autogenous shrinkage of mortar declines by 30%–40% in the first 60 days, and 20%–30% when the duration is extended to 90 days.

Additionally, the shrinkage of concrete is influenced by mineral admixtures. An appropriate amount of FA or GGBFS with reasonable fineness is used to replace part of the cement, which can decrease the early-age autogenous shrinkage of concrete [58, 59]. Results in [30] report that volume expansion is observed when GGBFS cement is used. Results in [60] show that FA has an inhibiting effect on autogenous shrinkage due to the deceleration of the reduction of internal humidity in the matrix.

1.3.4 Increasing the Tensile Strength

When shrinkage occurs in concrete under restrained conditions, restraint stress occurs. If the internal stress exceeds the tensile strength of the concrete, it is likely to crack, allowing the external air, water, and other chemical components to penetrate the concrete interior, reducing the durability of the concrete and affecting the service life of the cement material [61, 62]. So whether the concrete has superior tensile strength, or faster tensile strength growth rate, is one of the important indicators to measure the cracking resistance of concrete.

Some supplementary cementitious materials, such as silica fume, have very small particles so that silica fume particles can fill in the spaces between concrete cement particles, promoting pore size refinement and matrix densification in concrete and effectively improving the bond strength between aggregates and paste in concrete. In addition, silica fume can react with the generated calcium hydroxide and provide additional calcium silicate hydrates (C–S–H), which facilitates the increase of tensile strength [63]. Besides, concrete mixed with the proper proportion of FA has also been shown to have superior mechanical properties.

The addition of nanosized material is also beneficial to improve the tensile strength of concrete, which can be used as seeds in concrete to provide nucleation sites for the formation of cement hydration products and possess the effect of accelerating cement hydration, thus improving the early strength of concrete. Such as nano-$CaCO_3$ particles, which can bind to the surface of tricalcium silicate particles in cementitious materials, resulting in the rapid growth of C–S–H, dense microstructure, and effective improvement of early-age strength [64].

The addition of fibers to concrete is also an effective way to reduce the potential of cracking at early age, and concrete reinforced with randomly distributed short fibers can enhance its toughness to prevent or control crack sprouting, expansion, or consolidation [6]. In addition, fibers in concrete can effectively limit the development of cracks by making the shrinkage strain of fiber reinforced concrete significantly smaller than that of ordinary concrete. When the tensile strength of concrete is insufficient, the already cracked areas in the concrete will not work properly. At the same time, the fibers perpendicular to the crack hinder further crack development, thus increasing the tensile strength [65].

In addition to what has been mentioned above, there are many ways to improve the tensile strength of concrete. In some specific cases, a combination of methods can be used to achieve more satisfactory expectations. Subsequent chapters will delve into the tensile strength of concrete in a variety of directions.

1.4 Objectives and Scope

The authors present systematically their experimental and theoretical research on the early-age cracking control on modern concrete in recent years in this monograph. Seventeen chapters were organized in this monograph, and the main contents are introduced briefly as follows.

Chapter 2 introduced the computational theories, research methods, and the corresponding test apparatus. It included the evaluaion on the early-age internal humidity, autogenous shrinkage, mechanical properties, tensile creep, and the cracking resistance under circumferential and uniaxial restrained conditions. In addition, the integrated criterion of cracking resistance was also introduced.

Chapter 3 presented investigations on the early-age cracking control on concrete with IRH, water-to-cement ratio (*w*/*c* ratio), and curing temperature. The prediction models for IRH under sealed and unsealed conditions were established to predict the IRH as a function of *w*/*c* ratio, critical time, and concrete age. The prediction models for autogenous shrinkage of early-age concrete considering the influence of curing temperature were established. Furthermore, investigations on the residual stress, stress rate, stress relaxation, and cracking age of concrete were conducted to evaluate the cracking resistance of early-age concrete. In addition, the cracking resistance of early-age concrete with different *w*/*c* ratios and curing temperatures were investigated, respectively.

Chapter 4 presented investigations on early-age cracking control of concrete reinforced with FA. The uniaxial tensile strength, tensile Young's modulus, compressive strength, and compressive Young's modulus were tested, and prediction models for uniaxial tensile strength and tensile Young's modulus were proposed. In addition, whether and how FA influenced steel ring strain, the residual stress development, the ratio of the maximum residual stress to the time-dependent splitting tensile strength, the stress relaxation, and the stress rate of HPC were also carried out. Besides, the temperature history, autogenous shrinkage, restrained stress, and tensile creep under adiabatic conditions, which were necessary parameters for a comprehensive understanding of the cracking potential of HPC with FA were conducted by utilizing a Temperature Stress Test Machine(TSTM).

Chapter 5 presented investigations on the early-age cracking control on HSC with GGBFS under both circumferential and uniaxial restrained conditions. The investigations on the free shrinkage, strain in the steel ring, residual stress, stress rate, and stress relaxation were conducted to evaluate the cracking resistance of concrete with GGBFS, respectively. Furthermore, the temperature history, autogenous shrinkage, restrained stress, and cracking resistance of concrete were also proposed.

Chapter 6 presented investigations on the early-age cracking resistance of concrete with silica fume. Four concrete mixtures with 0.33 water-to-binder ratio were prepared at different replacement levels of silica fume. In addition, the prediction model for autogenous shrinkage of early-age concrete considering the effect of different silica fume dosages was proposed.

Chapter 7 presented investigations on the early-age cracking control on concrete with 3D hooked-end steel fiber. Firstly, the early-age tensile creep behavior of concrete considering the amount of 3D hooked-end steel fiber and thermal treatment temperature was investigated. The prediction model for the tensile creep of concrete considering the influence of 3D hooked-end steel fiber and thermal treatment temperature was proposed. Secondly, analysis on autogenous shrinkage, tensile creep, temperature history, restrained stress, the ratio of stress to axial tensile strength, stress reserve, and integrated criterion of cracking resistance of concrete with different contents of 3D hooked-end steel fiber was conducted. Finally, the influence of curing temperature on the early-age cracking resistance of concrete with 3D hooked-end steel fiber under uniaxial restrained conditions was further investigated.

Chapter 8 presented investigations on the early-age cracking control on concrete with 5D hooked-end steel fiber. To achieve this, the effect of different steel fiber volume fractions on steel ring strain, residual stress, free shrinkage, stress rate, stress relaxation, and cracking potential of HSC was tested using ring test. Temperature evolution, autogenous shrinkage, and restrained stress of concrete with 5D hooked-end steel fiber were tested using TSTM test.

Chapter 9 presented investigations on the early-age cracking control on concrete with PP fiber. Firstly, the early-age autogenous shrinkage of concrete with different proportions PP fiber was investigated. The prediction model for autogenous shrinkage of concrete reinforced with PP fiber was established based on test results of ultrasonic velocity, which could be applied in actual projects quickly. Secondly, the early-age basic tensile creep, basic tensile creep coefficient, and specific tensile creep of concrete with different proportions PP fiber were investigated. A modified model for the prediction of the specific tensile creep applicable to fiber reinforced concrete was also established. Thirdly, the early-age cracking resistance of HPC with PP fiber under both uniaxial or circumferential restrained conditions was investigated.

Chapter 10 presented investigations on the early-age cracking control on HSC with PVA fiber under both circumferential and uniaxial restrained conditions. The free shrinkage, residual stress, stress rate, stress relaxation, and cracking potential of HSC with different proportions of PVA fibers were indicated. Moreover, autogenous shrinkage, restrained stress, and creep were also investigated by TSTM considering different temperature histories.

Chapter 11 presented investigations on the early-age cracking control on HSC with nano-$CaCO_3$ under both circumferential and uniaxial restrained conditions. The free shrinkage, residual stress, stress rate, stress relaxation, tensile creep, and cracking potential of HSC with different proportions of nano-$CaCO_3$ were demonstrated. Besides, the relationship between relaxation and creep was also investigated. Moreover, the temperature history, restrained stress, autogenous shrinkage, tensile creep, and simplified stress–strain failure criterion were also investigated by TSTM with different temperature histories.

Chapter 12 presented investigations on the early-age cracking resistance of HSC with crystalline admixture under circumferential restrained conditions. The mechanical properties, free shrinkage, residual stress, stress rate and cracking potential were determined. Stress relaxation was also investigated under circumferential restrained conditions.

Chapter 13 presented investigations on the early-age cracking control on concrete with MgO compound expansive agent. Firstly, the influence of MgO compound expansive agent on temperature, thermal strain, autogenous strain, and creep under the adiabatic temperature curing mode and uniaxial restrained condition was investigated. Secondly, a simplified stress–strain failure criterion based on the results of tensile strength, elastic modulus, and restrained cracking tests was investigated for estimating the safety of concrete under restrained condition.

Chapter 14 presented investigations on the early-age cracking control on concrete with TRI. The mechanical properties, temperature process, autogenous shrinkage, restrained stress, and tensile creep of HSC containing different TRI contents were tested. A simplified stress–strain failure criterion and a prediction model for autogenous shrinkage of HSC with TRI were proposed.

Chapter 15 presented investigations on the early-age cracking control on HSC with SRA under both circumferential and uniaxial restrained conditions. The residual stress, stress rate, stress relaxation, and the models for the free shrinkage of early-age concrete were proposed. The early-age temperature history, autogenous shrinkage, tensile creep, restrained stress, and cracking resistance of concrete with SRA were explored.

Chapter 16 presented investigations on the early-age cracking control on concrete with reinforcing bars. The bond strength and the slip corresponding to bond strength were studied considering concrete age and concrete strength. The prediction model for the bond stress–slip relationship between reinforcing bars and HSC of different ages was proposed. Besides, the temperature history, shrinkage, stress, and creep of HSC with reinforcing bars at early age were analyzed under uniaxial restrained conditions considering the reinforcement percentage and reinforcement configuration.

Chapter 17 presented investigations on the early-age cracking control on concrete with internal curing. Firstly, early-age cracking control on concrete internally cured with SAPs was investigated based on the comprehensive analyses of temperature, shrinkage, stress, and creep behavior. Besides, the development of residual stress, stress relaxation, and tensile creep of concrete internally cured with LWAs under circumferential restrained condition considering the *w*/*c* ratio were studied.

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Chapter 2
Techniques and Methods for Evaluating the Early-age Cracking Resistance of Modern Concrete

2.1 Introduction

The cracking of concrete has always been a prominent and urgent issue in practical engineering. The cracking resistance of concrete involves many aspects, which in turn correspond to different parameters. An in-depth study and evaluation of these parameters are necessary to improve the cracking resistance of concrete.

This chapter presented the computational theories, research methods, and the corresponding test apparatus related to cracking control on concrete, including (1) the evaluation on the internal relative humidity (IRH) based on digital resistance-based sensors [1, 2], (2) the evaluation on early-age autogenous shrinkage based on non-contact sensors [3, 4], (3) the evaluation on the mechanical properties which consists of compressive strength, tensile strength, static elastic modulus, and dynamic elastic modulus [5], (4) the evaluation on the tensile creep such as basic tensile creep, tensile creep coefficient, and specific tensile creep [6], (5) the evaluation on the cracking resistance of concrete under circumferential restrained condition, such as the calculation of residual stress, stress rate, theoretical elastic stress, and relaxed stress [7], and (6) the evaluation on the cracking resistance of concrete under uniaxial restrained condition, such as the calculation of temperature history, creep, and integrated criterion [8, 9].

2.2 Early-age Internal Relative Humidity in Concrete

2.2.1 Test Device and Method

Figure 2.1 shows the changes of temperature and IRH in concrete measured by the digital resistance-based sensors (DB4850-DB170-N). The nominal accuracy of temperature or humidity of this sensor was ± 0.3 °C or ± 1.8% relative humidity

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