Journal of Engineering Research and Reports

Volume 26, Issue 6, Page 298-306, 2024; Article no.JERR.117561
ISSN: 2582-2926

Development in the Study of Mechanical Prop-erties and Damage Constitutive Models of Rub-ber-Reclaimed Concrete

ShanShan Zhou [a*]

[a] *School of Civil Engineering and Transportation, North China University of Water Resources and Electric Power, Zhengzhou 450045, China.*

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: https://doi.org/10.9734/jerr/2024/v26i61181

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/117561

Review Article

Received: 18/03/2024
Accepted: 22/05/2024
Published: 28/05/2024

ABSTRACT

Advances in rubber-reinforced concrete technology and its applications in engineering are cru-cial for the thorough recycling and safe disposal of waste tire rubber and construction debris. Rubber-reinforced concrete (RAC) is a concrete material produced by substituting some fine and coarse aggregates with waste rubber particles and recycled aggregates. The incorporation of waste rubber particles endows RAC with distinctive mechanical properties and a distinct damage constitutive model. The mechanical properties of rubber recycled concrete mainly in-clude compressive strength, tensile strength, flexural strength, and elastic modulus. Compared to traditional concrete, RAC exhibits slightly lower compressive and flexural strengths but sig-nificantly enhanced tensile strength. This is due to the changes in mechanical properties caused by the softness and elastic properties of rubber particles. In addition, the addition of rubber particles can also improve the energy absorption capacity and impact resistance of concrete. On the other hand, in order to

**Corresponding author: Email: 19837496630@163.com;*

Cite as: *Zhou , S. (2024). Development in the Study of Mechanical Prop-erties and Damage Constitutive Models of Rub-ber-Reclaimed Concrete. Journal of Engineering Research and Reports, 26(6), 298–306. https://doi.org/10.9734/jerr/2024/v26i61181*

describe the damage behavior of rubber recycled con-crete, some constitutive models were studied. Common models include linear elastic model, plastic model, and damage model. The linear elastic model is suitable for describing the be-havior of rubber recycled concrete during the elastic stage; The plastic model is suitable for describing its deformation behavior during the plastic stage; The damage model can better describe the fracture and failure behavior of rubber recycled concrete, including shear damage, tensile damage, and compression damage. Tailored to the unique characteristics of RAC, these models consider the stiffness of rubber particles and the deformation characteristics of the binding materials, enabling accurate predictions of the stress-strain behavior of RAC. In conclusion, rubber-reinforced concrete possesses excellent mechanical and durability proper-ties, which can be accurately described and predicted using appropriate constitutive models. These findings are crucial for advancing the application and development of rubber-reinforced concrete.

Keywords: Rubber-reinforced concrete; mechanical properties; stress-strain behavior; damage constitutive model.

1. INTRODUCTION

Recycled Aggregate Concrete (RAC) is a concrete material prepared by replacing some coarse and fine aggregates with recycled aggregates and waste rubber particles, respectively. The preparation of rubber recycled concrete aims to solve the environmental problems of waste rubber and construction waste, and reduce dependence on natural resources. With the increasing demand for sustainable building materials, rubber recycled concrete is receiving more and more attention and research as an environmentally friendly material [1]. Compared with traditional concrete, rubber recycled concrete has some unique mechanical properties. The addition of waste rubber particles can improve the flexibility and toughness of concrete, thereby enhancing its seismic and crack resistance performance. In addition, rubber particles can also fill the pore space in concrete, reduce its density, thereby reducing the self weight of the structure and improving construction efficiency. However, the mechanical properties of rubber recycled concrete are influenced by the interaction and interface bonding between rubber particles and concrete matrix, so it is necessary to conduct in-depth research on its mechanical properties and behavior.

When studying the mechanical properties of rubber recycled concrete, an important indicator is its compressive strength. Research has shown that the compressive and flexural strength of rubber recycled concrete is usually slightly lower than that of traditional concrete, due to the elastic properties of rubber particles and the interaction between the interface and the concrete matrix [2]. However, the tensile strength of rubber recycled concrete is usually higher than that of traditional concrete, due to the flexibility of rubber particles and their ability to absorb energy. In addition, rubber recycled concrete also has good freeze-thaw resistance and durability, which is particularly important for building structures used in harsh environmental conditions.

The constitutive model is a mathematical model that describes the mechanical behavior of materials, which is crucial for understanding and predicting the mechanical properties of rubber recycled concrete. By using appropriate constitutive models, the stress-strain behavior of rubber recycled concrete can be simulated, providing a basis for engineering design and structural analysis. Researchers have proposed various types of constitutive models to describe the stress-strain relationship of rubber recycled concrete [3], which consider factors such as the stiffness of rubber particles, deformation of bonding materials, and interface effects. The commonly used constitutive models include elastic model, plastic model, damage model, and viscoelastic model. The selection of these models depends on the research purpose and the required accuracy. However, due to the complexity and nonlinear characteristics of rubber recycled concrete, researchers need to study a constitutive model suitable for this material and verify and improve the accuracy of the model through experimental testing.

In addition to the study of its mechanical properties and constitutive models, there are also other aspects of research underway. For example, researchers observe and analyze the microstructure of rubber recycled concrete to understand the interaction mechanism between rubber particles and concrete matrix. In addition, research has been conducted on the durability, thermal insulation, and acoustic properties of rubber recycled concrete [4]. Overall, rubber recycled concrete is a promising building material that can play an important role in environmental protection and sustainable construction. By conducting in-depth research on its mechanical properties and constitutive models, we can better understand and apply rubber recycled concrete, promoting its widespread application in the construction industry. However, further research is needed to address some challenges, such as interface strength and long-term durability between rubber particles and concrete matrix.

In this context, this article summarizes and summarizes the research on the mechanical properties and constitutive models of rubber recycled concrete. Through experimental testing and analysis of the mechanical properties of rubber recycled concrete by previous scholars, key parameters such as strength, stiffness, deformation performance, and durability can be evaluated. Meanwhile, by studying appropriate constitutive models, the mechanical behavior of rubber recycled concrete under different loading conditions can be described. These research results are of great significance for promoting the application and development of rubber recycled concrete, as well as promoting the realization of sustainable buildings.

2. RESEARCH ON MECHANICAL PROPERTIES OF RUBBER RECYCLED CONCRETE

2.1 The Influence of Rubber and Recycled Aggregate Content and Particle Size on the Mechanical Properties of Concrete

The research on rubber recycled concrete started relatively late in China, and rubber and recycled aggregates are not widely used in practical engineering. They have only been applied in a few pilot highway projects, such as the service area pavement at the entrance of the Hebei Shijiazhuang section of the Qingyin Expressway, which uses rubber concrete. This is also the largest section of rubber aggregate concrete pavement in China, with a total area of over 2000 square meters, and it is also the project with the largest amount of rubber particles. After recent years of research and development, breakthrough progress has been made in the study of the basic mechanical properties and frost resistance durability of materials such as rubber concrete, recycled concrete, and rubber recycled concrete [4].

Mechanical properties are one of the most fundamental properties of concrete and a prerequisite for its application in engineering. Strength, as an important mechanical performance parameter of concrete, has always been a focus of attention for researchers. Rubber not only provides essential daily and medical light industry rubber products for people, but also provides various rubber production equipment or rubber components to heavy industries and emerging industries such as mining, transportation, construction, machinery, electronics, etc. Research in the construction industry has shown that for rubber particles, regardless of particle size or morphology, the compressive strength, flexural strength, splitting tensile strength, and elastic modulus of recycled concrete will be reduced. The larger the content and particle size of rubber particles, the lower the strength of rubber recycled concrete [5-6]. The experiment generally uses rubber materials with particle sizes of 100 mesh, 1-2mm, and 2-4mm prepared from waste car tires. The physical and mechanical properties of rubber materials are shown in Table 1. Rubber and recycled aggregates are shown in Figs. 1 and 2. The dosage of rubber particles is the main factor affecting the mechanical performance test strength of rubber recycled concrete.

Wang Wenrui et al. [7] used recycled coarse aggregates with particle sizes of 5-15, 5-20, and 5-25 mm; The effects of rubber particle size and content on the mechanical properties of recycled concrete were studied by replacing natural fine aggregates with rubber powder of 20 mesh, 40 mesh, and 60 mesh, with dosages of 0%, 15%, and 30%, respectively. The results indicate that within a certain range, the addition of rubber reduces the compressive and flexural strength of recycled concrete; With the increase of rubber powder mesh, the strength of recycled concrete has been improved to a certain extent, but the impact on the flexural strength of concrete is not significant; As the size range of recycled aggregate gradation increases, the compressive strength improves, but the impact on the flexural strength of concrete is not significant. Wang Liankun et al. [2] prepared self compacting rubber recycled concrete with different dosages of recycled aggregates and rubber particles, and studied the working and mechanical properties of self compacting concrete under different substitution rates of the two materials. The results show that with the increase of recycled aggregate and rubber particle content, the workability and mechanical properties of self compacting concrete decrease to varying degrees; When the replacement rate of recycled aggregate is 100% and the replacement rate of rubber is 10%, the cubic compressive strength, axial compressive strength, and splitting tensile strength of concrete decrease by 31.4%, 31.7%, and 26.9%, respectively. Tantala et al. [8] found that the addition of rubber particles can improve the toughness and impact resistance of concrete, and within a certain range, the degree of improvement of both properties also increases with the increase of the addition amount. Moreover, the modification effect of adding larger rubber particles is better than that of smaller ones.

2.2 Measures to Weaken the Influence of Rubber on the Mechanical Properties of Concrete

In order to improve the adverse effects of rubber addition on recycled concrete, the mechanical properties of recycled concrete can be improved by modifying rubber or adding fibers with stable properties and low elastic modulus. Tamana et al. [9] modified rubber particles with three concentrations of NaOH solution, improving the mechanical properties of rubber concrete. It was found that the higher the concentration of NaOH solution, the better the modification effect. Liu et al. [10] compensated for the strength loss of rubber concrete by modifying rubber particles

Table 1. Performance indicators of rubber materials

Name	Apparent density (kg/m3)	Rubber content (%)	Fiber content (%)	Elastic modulus (MPa)
Rubber material	1020~1250	51.0	0.5	1.5

Fig. 1. Rubber particles

Fig. 2. Recycled aggregate

with silica. Through layer scanning of rubber concrete, it was found that the silica modification method reduced harmful pores in concrete. Yang Changhui et al. [11] found that the strength improvement effect of NaOH solution modified rubber particles on rubber concrete is more significantly affected by the water cement ratio and rubber content. The higher the water cement ratio, the higher the rubber content, and the more significant the strength improvement effect. When the rubber content is 5%, 10%, and 15%, the compressive strength of modified rubber concrete is only reduced by 1.3%, 7.1%, and 14.8% compared to ordinary concrete. Tuqa et al. [12] added polypropylene fibers to recycled concrete to improve its mechanical properties by 0.6%, resulting in a 15.2% and 11.6% increase in compressive strength for recycled concrete with 50% and 100% substitution rates. In addition, Karimi et al. [13] used rubber powder with a particle size of 60 mesh to be added to concrete in a mass fraction ratio of 1%, 2%, 4%, and 12%, and studied the influence of different rubber contents on the mechanical properties of rubber concrete. Finally, they found that under the conditions of rubber content of 1%, 2%, 4%, and 12%, the compressive strength of concrete decreased by 8%, 20%, 39%, and 74%, respectively.

At present, research on rubber recycled concrete mainly focuses on the particle size range of rubber content, which is 0.75mm-5.00mm. There is very little research on the performance of rubber particle recycled concrete. Based on the existing research [14-16], the addition (or modification) of rubber has a significant impact on the mechanical properties of concrete. Therefore, further research on the mechanical properties of rubber particle recycled concrete has important scientific research value.

2.3 The Impact of Strength, Stiffness, and Other Factors on the Mechanical Properties of Concrete

The research on the mechanical properties of rubber recycled concrete (RAC) involves multiple aspects, including strength, stiffness, deformation performance, and durability. Firstly, for the study of strength performance, strength is one of the important indicators for evaluating the performance of rubber recycled concrete. Researchers usually evaluate the strength characteristics of rubber recycled concrete through experimental tests such as compressive strength, tensile strength, and flexural strength. These tests can be conducted under laboratory conditions according to international standards such as ASTM, EN, etc. In addition, non-destructive testing methods such as ultrasonic testing and impact testing can also be used to evaluate the strength performance of rubber recycled concrete. Secondly, in terms of stiffness performance research, it refers to the material's ability to resist strain, usually represented by elastic modulus or stiffness coefficient. Researchers can evaluate the stiffness characteristics of rubber recycled concrete through compression tests, bending tests, etc. In addition, non-destructive testing methods such as dynamic elastic modulus testing can also be used to evaluate its stiffness performance.

In the study of deformation performance of rubber recycled concrete, the deformation performance of materials includes their ductility, shrinkage, and deformation ability. Researchers can evaluate the deformation performance of rubber recycled concrete through methods such as tensile testing, shrinkage testing, and deformation monitoring. In addition, its deformation behavior under different loading rates can also be studied, such as its deformation performance under static and dynamic loading conditions.

The durability of rubber recycled concrete refers to its long-term stability and durability under different environmental conditions. Researchers can conduct various experiments on the durability of rubber recycled concrete, including freeze-thaw resistance, sulfate corrosion resistance, chloride ion penetration resistance, etc. These experiments can be conducted by simulating exposure tests under different environmental conditions.

In addition, the mechanical properties of concrete can also be explored from aspects such as structural performance research and sustainability assessment. In addition to the mechanical properties of materials, researchers also focus on the structural performance of rubber recycled concrete. They study the application of rubber recycled concrete in different structural systems, such as beams, columns, slabs, and bridges. Through experimental testing and numerical simulation, the bearing capacity, stiffness, and deformation behavior of rubber recycled concrete structures can be evaluated. Sustainability assessment refers to the use of rubber recycled concrete as an environmentally friendly material, and its sustainability assessment is also a part of research. Researchers evaluate the sustainability performance of rubber recycled concrete in resource utilization, energy consumption, carbon emissions, and environmental impact through methods such as Life Cycle Assessment (LCA).

When studying the mechanical properties of rubber recycled concrete, a large number of experimental tests and data analysis are usually required. These experiments can be conducted according to international standards to ensure comparability and reliability of the results. In addition, computer simulation and numerical analysis can be used to gain a deeper understanding of the mechanical behavior of rubber recycled concrete. It should be pointed out that although rubber recycled concrete has potential in the field of sustainable construction, there are still some challenges and limitations. For example, the interface strength issue between rubber particles and concrete matrix, long-term durability performance, and feasibility of large-scale production and application. Related research is constantly evolving to address these issues and promote the practical application of rubber recycled concrete, which remains a broad and complex field with many unresolved issues and challenges. Therefore, continuous research and exploration are crucial for promoting the application and development of rubber recycled concrete.

3. STUDY ON THE CONSTITUTIVE MODEL OF FREEZE-THAW DAMAGE IN RUBBERIZED RECYCLED CONCRETE

3.1 Classification of Models

The study of constitutive models for rubber recycled concrete (RAC) is a continuously developing field. The constitutive model is used to describe the stress-strain relationship of materials, which is crucial for understanding and predicting the mechanical behavior of materials [17]. When it comes to damage models for rubber concrete, they mainly include the following types: first, the Microplane model, a widely used damage model for concrete and other complex materials. This model describes the anisotropic damage behavior of materials by decomposing their strain and damage into components on multiple microscopic planes. Each micro plane has its own damage variables and damage evolution criteria, which can more accurately describe the damage process of rubber concrete; Next is the coupled damage plastic model, where rubber concrete often exhibits coupled damage and plastic behavior. The coupled damage plasticity model combines damage and plasticity theory to describe the plastic deformation and damage evolution of rubber concrete during the stress process. These models consider the influence of damage on plastic behavior and the influence of plastic strain on damage evolution, so as to more accurately predict the mechanical response of materials; Next is the temperature and humidity effect model, where the damage behavior of rubber concrete is influenced by environmental factors such as temperature and humidity. When establishing a damage model, it is necessary to consider the impact of these factors on the mechanical properties of rubber concrete and incorporate them into the model. For example, temperature and humidity can affect the strength, stiffness, and damage propagation rate of materials, so experimental research and model parameter correction are needed. Finally, numerical simulation methods can be used to predict and analyze material behavior after establishing a damage model for rubber concrete [18-19]. Common numerical simulation methods include finite element method, discrete element method, boundary element method, etc. These methods can simulate the mechanical behavior of rubber concrete under different scales and complex loading conditions, and provide information on stress, strain, damage distribution, and failure modes.

3.2 Research on Models

The freeze-thaw damage mechanics of concrete studies the entire process of concrete materials from micro crack initiation, propagation, evolution to macroscopic crack formation and ultimate failure. The aim is to evaluate the degree of damage to concrete structures by establishing the concrete damage evolution equation and the concrete damage constitutive relationship, in order to determine their operating status and stability [20]. The constitutive theory of concrete has also become an important basis for the research and design of concrete materials and structures [21], and has received widespread attention from concrete mechanics workers in recent years. Based on a large amount of experimental research and theoretical analysis, scholars have proposed various forms of concrete constitutive models, among which the more typical ones include the Zhenhai constitutive model [3], the segmented damage model [22], and the GB50010-2010 constitutive model [23].

On the basis of existing classical concrete damage constitutive models [24-25], Ji Xiaodong et al. [26] defined the damage variables by Poisson's ratio and elastic modulus in the damaged state, and established a concrete freeze-thaw damage constitutive model in combination with existing theoretical models. Long Guangcheng et al. [27] established a constitutive model for concrete damage after freeze-thaw cycles based on statistical damage theory and combined with the evolution law of freeze-thaw damage. Wang et al. [28] established a macroscopic and microscopic coupled damage model for concrete under freeze-thaw cycle load coupling based on the Lemaitre strain equivalence assumption. Bai Weifeng et al. conducted uniaxial compression tests on recycled concrete cubes subjected to different freeze-thaw cycles (N=0, 25, 50, 75, 100, 125, 150), and studied the effect of freeze-thaw cycles on the stress-strain curve of recycled concrete. They revealed the influence of freeze-thaw cycles on the peak stress, peak strain, and elastic modulus of recycled concrete. On this basis, a constitutive model and mathematical expression of parameters for uniaxial compression of recycled concrete considering the number of freeze-thaw cycles were established. The characteristic parameters showed obvious regular changes, and the experimental results have certain reference value for the application and research of recycled concrete [29].

Dong et al. [30] proposed a stress-strain constitutive relationship formula for steel fiber reinforced rubber concrete, including the rising and falling sections, based on the model of GB50010-2010 [23], considering the influence of rubber and steel fiber content. However, the curve obtained from the proposed model is only applicable to the volume substitution rate of rubber content within the range of 20%. Qiu Jianhui et al. [31] studied the influence mechanism of rubber modification on the stress-strain performance of recycled concrete. Using rubber content as a variable, the recycled concrete was uniformly heated to different temperatures in a high-temperature environment. The stress-strain relationship curve of recycled concrete after high temperature was tested, and the strength, elastic deformation, and plastic deformation performance of rubber recycled concrete under normal temperature conditions were analyzed. The results show that the ductility of recycled concrete increases with the increase of rubber particle content; When the rubber particle content is 4%, the performance degradation of strength, elastic deformation, and plastic deformation is minimal; In addition, the addition of rubber particles improves the cracking performance of recycled concrete at high temperatures.

At present, the academic community has conducted a large amount of research on rubber concrete, recycled concrete, and rubber recycled concrete, and has a certain theoretical basis for understanding the basic properties of materials. Research methods and technologies are gradually maturing. However, research results on the performance of concrete mixed with rubber particles and recycled aggregate are limited, and existing research methods have not reached a consensus. Therefore, it is extremely important to further expand the research on the freeze-thaw damage constitutive model of rubber recycled concrete.

4. CONCLUSION

Sustainability. The use of rubber and recycled aggregates can promote the reuse and recycling of waste. Rubber comes from waste materials such as car tires, while recycled aggregates come from discarded concrete or construction waste. By converting these waste materials into useful concrete components, the demand for raw materials can be reduced, the exploitation of natural resources can be reduced, and the impact of waste on the environment can be reduced.

Energy absorption and shock absorption performance. The addition of rubber particles can improve the energy absorption and seismic performance of concrete. Rubber has high bending and tensile deformation ability, which can absorb and disperse energy when subjected to external impacts or vibrations, thereby reducing the vibration and vibration of the structure.

Anti cracking performance. The elasticity and flexibility of rubber can improve the crack resistance of concrete. The addition of rubber particles can reduce the generation and propagation of cracks in concrete, and improve the tensile strength and crack resistance of concrete.

Thermal conductivity. The addition of recycled aggregates can improve the thermal conductivity of concrete. Recycled aggregates usually have a lower thermal conductivity, which can reduce the thermal conductivity of concrete, reduce thermal bridging effects, and thus improve the energy efficiency of buildings.

Reduce settlement and shrinkage. The use of rubber and recycled aggregates can also reduce the settlement and shrinkage of concrete. The elastic properties of rubber particles can reduce the shrinkage deformation of concrete under dry and wet conditions, thereby reducing the risk of structural cracking.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Wang Jiaqing, Dai Qingli, Si Ruizhe, et al. Mechanical, durability, and microstructural properties of macro synthetic Polypropylene (PP) fiber-reinforced rubber concrete [J]. Journal of Cleaner Production. 2019;234:1351-1364.
2. Wang Liankun, Liu Jie, Lin Wenhao, et al. The workability and mechanical properties of self compacting rubber recycled concrete [J]. Journal of Wuyi University (Natural Science Edition). 2023;37(02):43-48.
3. Guo Zhenhai, Zhang Xiuqin, Zhang Dacheng, et al. Experimental study on the stress-strain curve of concrete [J]. Journal of Building Structures. 1982;(1):1-12.
4. AI-Fakih A, Nor Z.M, Basha S.I, et al. Characterization and applications of red mud, an aluminum industry waste material, in the construction and building industries, as well as catalysis [J]. Chemical Record. 2023;23(5):e202300039.
5. Pacheco-Torres R, Cerro-Prada E, Escolano F, et al. Fatigue performance of waste rubber concrete for rigid road pavements [J]. Construction and Building Materials. 2018;176:539-548.
6. Gurunandan M, Phalgun M, Raghavendra T, et al. Mechanical and damping properties of rubberized concrete containing polyester fibers [J]. Journal of Materials in Civil Engineering. 2019;31(2): 04018395.
7. Wang Wenrui, Zhu Rongchen, Zhu Huanbin, et al. Experimental study on mechanical properties of rubber recycled concrete [J]. Guangdong Civil Engineering and Architecture. 2023;30(09):111-113+116.
8. Tantala MW, Lepore JA, Zandi I, et al. Quasi-elastic behavior of rubber included concrete inproceedings 12th International Conference on Solid Waste Technology and Management [C]. Philadelphia: University of Pennsylvania. 1996;163-169 .
9. Tamanna K, Tiznobaik M, Banthia N, et al. Mechanical properties of rubberized concrete containing recycled concrete aggregate [J]. ACI Materials Journal. 2020; 117(3):169-180.
10. Liu Xiaoyan, Liu Li, Lyu Kai, et al. Enhanced early hydration and mechanical properties of cement-based materials with recycled concrete powder modified by nano-silica [J]. Journal of Building Engineering. 2022;50:104175.
11. Yang Changhui, Tian Yi, Wang Lei, et al. The effect of NaOH pretreatment on the properties of rubber concrete [J]. Civil and Environmental Engineering. 2016;38(02): 44-50.
12. Ahmed T, Ali A, Zidan R, et al. Properties of high strength polypropylene fiber concrete containing recycled aggregate [J]. Construction and Building Materials. 2020; 241(C):118010.
13. Karim HR, Aliha MRM, Khedri E et al. Strength and cracking resistance of concrete containing different percentages and sizes of recycled tire rubber granules [J]. Journal of Building Engineering. 2023; 67:106033.
14. Li X, Li L, Zheng Y, et al. A study of the compressive behavior of recycled rubber concrete reinforced with hybrid fibers [J]. Materials. 2023;17(3):4731.
15. He Liang, Huang Yong, Feng Chang, et al. Research progress on the properties of rubber concrete and surface modification of rubber powder [J]. Silicate Bulletin. 2018;37(08):2483-2489+2496
16. Elzeadani M, Bompa DV, Elghazouli AY. Monotonic and cyclic constitutive behaviour of rubberised one-part alkali-activated concrete [J]. Construction and Building Materials. 2023;368:130414.
17. Penttala. Surface and internal deterioration of concrete due to saline and non-saline

freeze-thawloads [J]. Cement Concrete Research. 2006;36(5):921-928.
18. Bravo M, Brito J. Concrete made with used tyre aggregate: durability-related performance [J]. Journal of Cleaner Production. 2012;25:42-50.
19. Malhotra V. Cement [J]. Concrete and aggregate. 1982;4(1):3-23.
20. Bai WeiFeng. Peak research on concrete damage mechanism and mechanical properties of saturated concrete [D]. Dalian: Dalian University of Technology; 2008.
21. Wang Haitao, Fan Wenxiao, Liu Tianyun, et al. Experimental study on uniaxial dynamic compressive performance of fully graded concrete after freeze-thaw cycles [J]. Journal of Water Resources. 2015; 46(06):732-738.
22. Qian Jicheng, Zhou Jianfang. Two types of damage models for concrete and their applications [J]. Journal of Hohai University. 1989;(03):40-47.
23. GB 50010-2010 Code for Design of Concrete Structures [S]. Beijing, China Construction Industry Press; 2015.
24. Dougill JW. On stable progressively fracturing solids [J]. Zeitschrift fur angewandte Mathematik und Physik ZAMP. 1976;27(4):423-437.
25. Lemaitre J. How to use damage mechanics [J]. Nuclear Engineering and Design. 1984;80:233-245.
26. Ji Xiaodong, Song Yupu, Liu Jian. Research on the constitutive model of concrete freeze-thaw damage [J]. Journal of Computational Mechanics. 2011;28(3): 461-467.
27. Long Guangcheng, Liu He, Ma Kunlin, et al. A constitutive model for uniaxial compressive damage of concrete considering freeze-thaw effects [J]. Journal of Central South University (Natural Science Edition). 2018;49(8): 1884-1892.
28. Wang Boxin, Fei Qing. Damage constitutive models of concrete under the coupling action of freeze-thaw cycles and load based on Lemaitre assumption [J]. Construction and Building Materials. 2018;173:332-341.
29. Bai Weifeng, Wang Weili, Yuan Chenyang, et al. Experimental study on stress-strain relationship of recycled concrete under freeze-thaw environment [J]. Concrete. 2021;(06):9-12.
30. Dong S, Zhao Q, Zhu H. Mechanical properties and constitutive model of steel fiber-reinforced rubberized concrete [J]. Construction and Building Materials. 2022; 329:126720.
31. Baoding Jing, Qiu Jianhui, Yao Minghui, et al. The effect of rubber modification on the stress-strain performance of recycled concrete [J]. Materials Research and Application. 2023;17(01):166-170.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/117561