EXPERIMENTAL ANALYSIS OF ENHANCED MECHANICAL PROPERTIES IN STEEL FIBER- REINFORCED RECYCLED CONCRETE

ZHANG LI

SULTAN IDRIS EDUCATION UNIVERSITY

2025

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ZHANG LI

THESIS PRESENTED TO QUALIFY FOR A DOCTOR OF PHILOSOPHY

FACULTY OF TECHNICAL AND VOCATIONAL
SULTAN IDRIS EDUCATION UNIVERSITY

2025

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ACKNOWLEDGEMENTS

Thanks to my supervisor during the process of writing my dissertation, my supervisor Assoc. Prof. Dr. Mohamed Nor Azhari Azman gave me a lot of academic guidance and advice which helped me to complete my dissertation research successfully. Thanks to Assoc. Prof. Dr. Ramadhansyah Putra Jaya for his help and encouragement in writing my thesis. I am thankful to the staff of the Faculty of Technical and Vocational for their support and help in my thesis. I would also like to thank my other form Dr Zhenpeng Yu and Mr Zhiqing Zhao, and my friends and colleagues for all the help they gave me. Finally, I would like to thank my family for their support and dedication to my studies and for supporting me to complete my studies successfully!

ABSTRACT

Environmental protection and recycling of resources are issues of international concern today, recycled concrete, as a green building material, can promote the healthy development of the construction industry. This study aims to assess the mechanical enhancements in recycled concrete when reinforcing with varying steel fiber volumes, evaluating its potential for broader structural applications. By reinforcing the recycled coarse aggregate, the addition of steel fibers, and the study of improved mechanical properties of the recycled concrete improved scale. Designing a comparative experiment to analyze mechanical properties of three different coarse aggregate steel fiber-reinforced recycled concretes, steel fiber volume rates were 0%, 1%, 2%, and 3%, and strength class was C30, a total of 144 pieces of 100mm x 100mm x 100mm cubic specimens. Analyzing uniaxial compression, split tension, shear, and biaxial compression-shear forces, the study of damage mechanisms and stress-strain curve performance, establishing the corresponding constitutive relationship model, measurement of displacement and strain fields by Digital Imaging Correlation (DIC) technology, observation of force damage. The research finds that strengthening recycled coarse aggregates can improve interface structure between the matrix and aggregates, significantly enhanced the strength of recycled concrete, it can achieve the strength value of conventional concrete. Adding steel fibers improves the weak interfacial transition zone, enhances stability, and increases toughness, thereby delaying damage evolution, the mechanical properties improve as the volume fraction of steel fibers increase. The study concluded that the reinforcement of recycled coarse aggregates and the incorporation of steel fibers can reduce stress-induced damage, and the improvement in the mechanical properties of recycled concrete by steel fibers is superior to that of conventional concrete, and the optimal volume fraction of steel fibers can be selected as 2%. The results implicated that strengthening recycled coarse aggregates can replace natural coarse aggregates, meeting the requirements of construction engineering.

ANALISIS EKSPERIMEN TERHADAP PENINGKATAN SIFAT MEKANIKAL DALAM KONKRIT KITAR SEMULA YANG DIKUATKAN DENGAN GENTIAN KELULI

ABSTRAK

Pemeliharaan alam sekitar dan penggunaan semula sumber merupakan isu yang mendapat perhatian antarabangsa pada masa kini. Konkrit kitar semula, sebagai bahan binaan hijau, dapat memacu perkembangan sihat industri pembinaan. Kajian ini bertujuan untuk menilai peningkatan mekanikal dalam konkrit kitar semula apabila diperkuat dengan pelbagai jumlah gentian keluli, serta menilai potensinya untuk aplikasi struktur yang lebih luas. Melalui penguatan agregat kasar kitar semula dan penambahan gentian keluli, kajian ini menilai tahap peningkatan sifat mekanikal konkrit kitar semula selepas penambahbaikan. Reka bentuk ujian perbandingan untuk menganalisis sifat mekanikal konkrit kitar semula gentian keluli dengan tiga jenis agregat kasar yang berbeza. Kadar isipadu serat keluli yang digunakan adalah 0%, 1%, 2%, dan 3%, dengan kelas kekuatan C30. Sebanyak 144 spesimen, masing-masing berukuran 100mm x 100mm x 100mm, disediakan untuk ujian. Kajian ini menumpukan pada menganalisis mampatan uniaxial, ketegangan pecahan, ricih, dan daya mampatan-ricih dwipaksi. Ia meneliti mekanisme kerosakan dan prestasi lengkung tegasan-tekanan, memodelkan hubungan ontologi yang sepadan. Medan anjakan dan ketegangan diukur menggunakan teknologi Korelasi Imej Digital (DIC) untuk memerhati kecederaan daya. Penemuan Penyelidikan bahawa penguatan agregat kasar kitar semula memperbaiki struktur antara agregat dan matriks, meningkatkan kekuatan konkrit kitar semula dengan ketara, dan mampu mencapai nilai kekuatan konkrit biasa. Penambahan gentian keluli memperbaiki zon peralihan antara antara muka yang lemah, meningkatkan kekuatan dan meningkatkan ketangguhan, sekaligus melambatkan evolusi kerosakan.Sifat mekanikal bertambah seiring dengan peningkatan kadar isipadu gentian keluli. Kesimpulan kajian menunjukkan bahawa penguatan semula agregat kasar kitar semula dan penambahan gentian keluli mengurangkan kerosakan akibat beban. Penambahbaikan sifat mekanikal konkrit kitar semula oleh gentian keluli adalah lebih baik berbanding konkrit biasa, dengan kadar isipadu gentian keluli yang optimum adalah 2%. Kajian mencadangkan bahawa agregat kasar kitar semula yang telah diperkukuh boleh menggantikan agregat kasar semula jadi dan memenuhi keperluan kejuruteraan pembinaan.

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LIST OF ABBREVIATIONS

ACCA	Surface Cracks in Coarse Aggregates
ACI	Alloy Casting Institute
BCS	Japan Construction Industry Association
BF	Teel Fiber Used in This Paper is Double-ended Hook Type
CABR	China Academy of Building Research
CR	Crack Resistance
CRA	Reinforcement of recycled coarse aggregate to produce recycled concrete
CS	Compressive Strength
CSS	Compressive Shear Strength
DIC	Digital Image Correlation
FPD	Failure Pattern in Parallel Shear Direction
FPZ	Fracture Process Zone
FVD	Failure Pattern in Vertical Shear Direction
G	Grade
GR	Aggregate Grading
H	High Quality
HKSAR	Hong Kong Special Administrative Region
JGJ	Construction industry construction standards

JGJT	Construction industry construction standards/recommended
JISA	Japanese Industrial Standard
JISTRA	Japanese Industrial Standards
L	Low Quality
M	Medium Quality
MCCA	Moisture Content of Coarse Aggregates
MD	Mechanical Damage
MOST	Ministry of Science and Technology
N	Number
NA	Natural Coarse Aggregate to produce concrete
NDRC	China's National Development and Reform Commission
NUAA	Nanjing University of Aeronautics and Astronautics
PVA	Polyvinyl Alcohol
QUT	Qingdao University of Science and Technology
RA	Recycled Coarse Aggregate to produce recycled concrete
RILEM	International Federation for Experimental Research on Materials and Structures
RRL	Rabbit Reticulocyte Lysate
SEM	Scanning Electron microscope
SFRC	Steel Fiber Reinforced Concrete
SS	Shear Strength
TS	Tensile strength

CHAPTER 1

INTRODUCTION

1.1 Research Background

According to statistics, the global production of construction waste exceeds 1 billion tons annually. Population-dense countries like China, India, and the United States are the major sources of construction waste worldwide (Wang, Yan, Fu, & Kasal,2021). The indiscriminate dumping or landfilling of construction waste severely impacts the environment, contaminating land and water sources, and generating dust that degrades air quality, this practice is detrimental to the sustainable development of building materials (Munir, Kazmi, Wu, Lin, & Ahmad, 2022). Therefore, recycling construction waste into recycled concrete is of great significance for reducing environmental pollution and promoting the circular use of building materials.

Concrete is a composite material, mainly composed of coarse aggregate, fine aggregate, cement cementitious materials, and water, an artificial stone formed through a chemical reaction. In the course of engineering use, according to the actual needs, choose to add a certain amount of additives to meet different needs (Guo, 1997). Compared to other building materials, for example: steel, wood, aluminum, stone, glass, etc. the advantage of concrete materials is that they can be adapted to local conditions, are locally sourced materials, have strong plasticity, good integrity, high-stress performance, good durability, high compressive strength, etc., easy to take the material so the cost is low.

Because of the superiority of concrete material itself, it is the main building material that is currently used in civil engineering. Not only is it widely used in housing construction projects, but also municipal infrastructure, road and bridge projects, water conservancy dam projects, underground tunnels, and other projects, it is also an irreplaceable main building material (Yu,2020). Analysis of the mass ratio of concrete shows that in ordinary concrete, cement accounts for 12%, coarse and fine aggregate accounts for 80%, and water accounts for 8%. From the mass ratio of materials, aggregate consumption accounts for a large part of concrete raw materials (Zhang, 2015). In the past 20th century, concrete has become an irreplaceable building material in civil engineering. In today's 21st century, concrete is still in an important position in civil engineering, and the foundation of building engineering, water conservancy dams, and municipal infrastructure can't do without concrete.

The advantages of concrete are recognized by the world, and there are both advantages and disadvantages. The disadvantages are that it is heavy, easy to crack, and has a long production cycle, especially the construction waste generated is difficult to treat, which has a great impact on the environment (Collivignarelli et al., 2020). At present, the impact of concrete materials on the environment is subject to more and more supervision, especially in the current environment of reducing carbon emissions. From the production process to the molding and use, and then to the later disposal, the utilization of natural resource aggregates and water is subject to layers of supervision. Some problems not only involve the national level, but also rise to international issues and become international political themes (Filippo, Karpman, & Deshazo, 2019). In terms of industry, we should actively solve our problems (Schneider, 2019). At present, waste concrete is mainly used to produce recycled aggregate. From the analysis of the current market situation, the technology and ecological efficiency of producing recycled aggregate. The current technical level can't realize the large-scale reuse of waste concrete. Because of these problems, increasing the research on recycled aggregate can improve the utilization rate of recycled aggregate and reduce the use of natural resources. Therefore, it is a very valuable thing to study how to reduce the carbon emission of concrete and improve the service life of waste. Therefore, the research on the complete recycling of concrete has become unprecedented and meaningful.

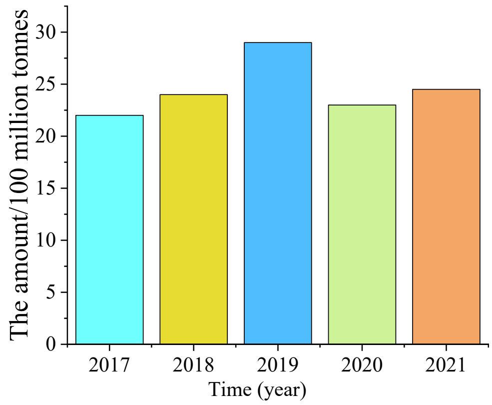
Recycling refers to the separation and extraction of useful substances from wastes, which are processed into reusable products by physical or mechanical processing. Such as the recycling of waste glass and nonmetal. Recycling is the process of turning waste products into reusable materials. Different from recycling, recycling only refers to the second use of an item or product. Recycling can not only reduce waste but also save natural resources. The research on recycled concrete aims to increase its recycling rate, improve its life cycle, and at the same time meet the use requirements. With the improvement of recycling technology of waste concrete, the life cycle of concrete is also changing, from the original linear life cycle from cradle to grave to the circular life cycle from cradle to cradle. From this analysis, it is concluded that the recycling of concrete, the life cycle management of structures, and the design of new structures are interrelated and inseparable (Atef, Gomaa, & Mostafa, 2022). The evolution of this cycle can be explained by the circular economy, which is used to cope with the increasing impact of waste on the environment (such as vision) to a certain extent. At present, all countries in the world are paying extensive attention to the policies and industrial development strategies of different countries (Kylili and Fokaides, 2017; Nußholz, Nygaard, & Milios, 2019).

With the rapid development of the social economy, concrete is the preferred building material in the world, whether it is housing, sanitation, or infrastructure, and it also promotes the development of the construction industry. In the process of social development, human beings' requirements for living environments are getting higher and higher, and the requirements for harmonious coexistence between man and nature are getting higher and higher. With the rapid development of the construction industry, the building material concrete is a kind of building material in great demand (Yu, 2020). The large demand for concrete materials also leads to the fact that coarse aggregate is basically a non-renewable resource, and the quantity of natural stones and sand used as raw materials for concrete is also increasing. To obtain a large quantity of natural stones, over-exploitation is needed, which destroys the natural environment and violates the harmonious development between man and nature. Internationally, natural disasters, such as earthquakes, floods, typhoons and wars, have caused a continuous increase in waste concrete, which has brought great pressure on the environment.

Due to the limitation of concrete service life, to ensure the safe use of buildings, it is a necessary process to demolish old buildings and build new ones. According to statistics, China produces nearly 3 billion tons of construction waste every year（Liu, Long, & Li, 2020). Construction waste is an inert waste. If the construction waste is directly buried or treated in the open air, it will be a waste of potential resources. With the rapid development of our country, the amount of waste concrete is increasing year by year. In the past two years, it has slowed down because of the epidemic situation, but the amount of waste concrete cannot be ignored. As shown in Figure 1.1, the amount of waste concrete in China in recent years (Li, 2019).

Figure 1.1

Amount of Waste Concrete in Recent Five Years



There is more and more construction waste. How to solve such a large amount of construction waste, if simply landfilled or transported to remote areas for open stacking, will not only occupy and destroy fertile land, increase freight, and cause dust pollution, but also not meet the requirements of current environmental protection development (Liu, Long, & Li,2020). How to ensure the healthy and sustainable development of the construction industry. The reuse of building waste materials can effectively solve these two problems. Recycling concrete not only responds to environmental protection, but also plays an important role in ecological sustainable development and maximum use of resources (Hemida, Abdalla, & Fouad, 2023). It is of great social significance and economic value to study the application of recycled concrete in civil engineering such as roads, bridges, water conservancy, and buildings. Researchers at home and abroad are doing more and more research on recycled concrete.

1.2 Research Significance

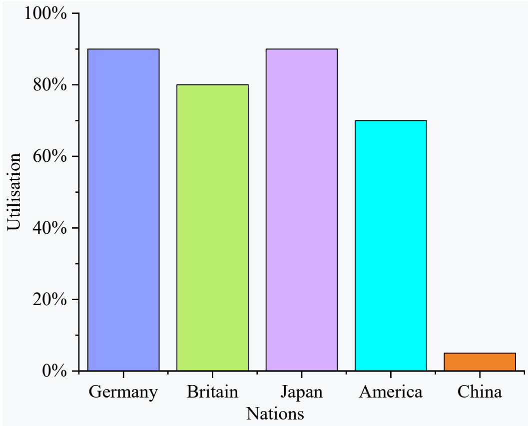
Since the 21st century, with the rapid development of the world economy, the population has continued to grow, and housing and infrastructure construction has increased rapidly. For the raw materials of concrete, the demand for sand and gravel has brought huge consumption of natural resources, which has aggravated the shortage of natural resources. According to statistical analysis, more than 5 billion tons of sand, gravel, clay, lime, and other raw materials are mined every year in China to produce cement and concrete. The huge demand for sand and gravel leads to over-exploitation of rocks. In China, the sources of fine aggregate are mainly river sand and mountain sand, and the sources of coarse aggregate are mainly pebbles and crushed stones. Mining rocks will inevitably cause damage to many woodlands and mountains, endanger ecological balance, and then lead to environmental damage (Li,2019).

Nowadays, the energy problem is very serious in the world, and the development of the construction industry is also facing the problem of energy crisis. As one of the most important building materials in building construction, concrete is restricted in the use of raw materials. On the one hand, it is faced with great harm to nature caused by sand and gravel mining, such as tree cutting, landslide and debris flow caused by massive mining of stone, and natural disasters such as river water pollution and flooding caused by sand mining. Human beings have paid a heavy environmental price because of their excessive demand for nature (Wu, Ren, & Ji, 2022). Smog weather is an event that has a serious impact on people's lives in recent years, and the rise of PM2.5 (fine particulate matter) is closely related to urban construction (Yang &Ye, 2020).

On the other hand, the increasing amount of construction waste has caused heavy pressure on the natural environment. How to deal with construction waste reasonably and effectively, realize the reuse and recycling of resources, and respond to the concept of low-carbon, emission reduction, and green sustainable development is a problem that we should consider. The recycling of concrete conforms to the sustainable development plan advocated by the international community today and plays an important role in this grand plan of sustainable development, which not only realizes the sustainable development of the construction industry but also reduces the exploitation and destruction of natural resources and avoids the impact of secondary disasters caused by environmental destruction. The exploitation of stones and sand not only damages the mountains and rivers, but also brings environmental hazards, damages the habitat and growth environment of some animals and plants, and artificially destroys the richness and diversity of biological species. Statistical analysis from the literature, the resource utilization rate of waste concrete in China is less than 5%, utilization rates as high as 97% in countries such as Europe and the United States (Li,2019), as shown in Figure 1.2. Except for a small amount used for engineering backfilling and recycling, most of them are still simply stacked. There is still a big gap between Western developed countries and the reuse of waste concrete resources.

Figure 1.2

Utilization Rate of Waste Concrete in Various Countries



How to reclaim and recycle waste concrete, has become a major mainstream direction for the treatment of waste concrete today, and all countries are actively studying recycled concrete. Germany, Japan, the United States, the Netherlands, Denmark, and other EU countries are recycled concrete development and utilization of relatively early countries, scrap concrete is processed to obtain recycled concrete aggregates, which are mainly used in road construction (De & De, 2022). They already have relatively mature relevant laws and regulations, and some countries have realized "resource utilization", "harmlessness" and " yield quantification ".

China's research on the recycling and reuse of waste concrete started relatively late. The common method for handling construction waste generated from the demolition of old buildings, as well as new construction and renovation projects, is outdoor open-air stacking or landfilling. Transporting and landfilling such massive amounts of construction waste incur significant economic costs. Furthermore, the transportation and landfilling of construction waste generate large amounts of dust, leading to environmental pollution and significantly impacting air quality. According to relevant data, the amount of discarded construction concrete in China increases at a rate of 8% annually (Huang & Chen, 2015). In the current scenario of extremely low recycling rates, these wastes not only occupy vast amounts of land but also exert tremendous pressure on the environment. Therefore, finding safe methods to handle construction waste has become an urgent issue that needs to be addressed.

Waste concrete is converted into recycled aggregates through multi-step crushing, screening, and other processes, which are then used to produce recycled aggregate concrete. This process not only effectively reduces the demand for natural aggregates, thus saving resources and costs, but also realizes the reuse of waste resources and promotes the development of the circular economy. At the same time, the use of recycled concrete also reduces the environmental pollution caused by the transport and landfill of waste concrete, which is less burdensome to the environment. The recycled coarse aggregate in recycled concrete has mortar parcels and cement mortar agglomerates, which have rough surfaces with angles and internal cracks, leading to an increase in the internal porosity of the concrete, which affects its mechanical properties, especially in terms of compressive strength (Wu, Cheng, Zhong, Lai, & Chen, 2022).

This study first optimizes the gradation of recycled coarse aggregate and strengthens it with chemical slurry, then incorporates steel fibers to produce recycled concrete, the mechanical properties are analyzed to study the changes in mechanical performance. This study aims to improve the mechanical properties of recycled concrete and provide technical support and theoretical guidance for its application in engineering. By reinforcing the coarse aggregate of recycled concrete and adjusting its gradation, we can improve the strength of concrete, thus promoting the wide application of recycled concrete in the engineering field. This not only realizes the concept of waste reuse but also reduces the cost of transporting and landfilling waste concrete and reduces the demand for concrete raw materials. At the same time, this initiative helps to improve the environmental impact of waste concrete and reduce environmental pollution. Ideas consistent with sustainable development strategies, the initiative has a positive impact on nature, society, the economy, and the environment, promotes the efficient use of resources, and contributes to sustainable development.

1.3 Market Application Trends of Recycled Aggregate

1.3.1 International Application Trends of Recycled Concrete

As early as the1970s, the countries that started the research on recycled concrete began to pay attention to the research on the reuse of waste concrete. For example, some European countries, such as Germany, the Netherlands, Finland, Denmark, etc., according to the actual situation of each country, strengthen the management of waste concrete reuse and formulate many relevant incentives and penalties from the government level (Chen,2016). After the Second World War, Japan, the United States, and other countries, in the post-war reconstruction, actively promote the reuse of waste concrete. Recycled concrete researched in Russia, focusing on the study of mixing ratios of recycled concrete and the properties of recycled concrete (Zhang,2015).

Japan has a limited land area and scarce resources, while it is frequently hit by earthquakes. To meet the challenge of resource scarcity, the Japanese government passed legislation as early as 1977 and promulgated the Code for the Use of Recycled Aggregate and Recycled Concrete (Code,1977). The code requires mandatory delivery of construction waste to specialized treatment facilities for treatment to reuse the resources. This initiative resulted in a 98% recycling rate of waste concrete. In this way, Japan has effectively dealt with the problem of resource scarcity and has also achieved remarkable success in the circular economy. This initiative not only helps to reduce dependence on limited resources, but also promotes the effective use of waste resources and injects new vigor into the country's sustainable development.

The United States has been at the forefront of the use of recycled resources, and has long been among the countries that have proposed environmental labeling. Through national legislation, the US has established norms to promote the reuse of waste concrete. Based on the properties of recycled aggregates, waste concrete is widely used in areas such as road engineering and foundation treatment of structures. Currently, more than 20 states use recycled concrete in road construction projects, 26 states use recycled aggregates in multi-layer materials for road projects, and 4 states use recycled aggregates as sub-base materials for road projects. Among them, 15 states have formulated relevant specifications and guidelines to ensure the smooth application of recycled concrete (Jin&Chen,2019). To promote the development of the recycled concrete industry, the U.S. government has also enacted the Superfund Act, which provides important legal support for the production, application, and environmental protection of recycled concrete. These initiatives have not only effectively solved the problem of waste concrete disposal, but also promoted the practice of sustainable development and resource recycling, laying a solid foundation for future environmental and economic development (Yang &Ye, 2020).

In the early 1980s, Europe began to pay attention to the disposal of construction waste and rubbish. The Netherlands, as a densely populated country facing limited national resources, started to research recycled concrete as early as that time. The Netherlands formulated early specifications related to recycled concrete and stipulated that the replacement rate of recycled aggregates should not exceed 20%. In addition, the Netherlands also specified that recycled coarse aggregates could be designed to prepare recycled concrete according to the proportion of natural aggregates. These initiatives demonstrate the early research and specification development in the field of recycled concrete in the Netherlands, which laid the foundation for the country's subsequent development in the field of sustainable construction. In 1996, the national construction waste emissions in the Netherlands amounted to 15 million tons, of which the recycling rate of waste concrete was already more than 90%. And after the ban on burying construction waste in the Netherlands in 1997, this figure reached almost 100%

(Zhao, 2020). This means that the Netherlands has made great progress in the treatment of construction waste, and most of the waste concrete has been reused efficiently, contributing positively to the sustainable use of resources and the protection of the environment.

Since 1996, the UK has implemented a construction waste landfill tax, as well as providing policy support and financial guidance to construction waste treatment plants to strongly promote the use of recycled aggregates in concrete construction (Li, 2022). This initiative aims to promote the effective treatment and reuse of construction waste, thus reducing the dependence on natural resources and the environmental load, and making a positive contribution to the sustainable development of the construction industry.

Since 1980, recycled concrete has been gradually introduced in Australia. It is estimated that about 400,000 tons of waste concrete are available annually in Sydney and 350,000 tons in Melbourne. The compressive strength of the old concrete in recycled concrete, the flake index, and the content of soft materials in recycled aggregates have important effects on the modulus of elasticity. Of these factors, the flake index and the soft matter content of recycled aggregates have the most significant effect on the modulus of elasticity. If the recycled aggregates can meet the quality standards of concrete aggregates, the performance of recycled concrete made from recycled aggregates is like that of ordinary concrete, and the recycled aggregates can completely replace traditional aggregates (Liu et al., 2007). These findings indicate that the widespread use of recycled concrete in Australia is feasible and is expected to make a significant contribution to the sustainable development of the construction industry.

In Russia, the focus was on the properties of recycled concrete ratios and fresh concrete. In their research in this area, they found that the compressive strength and modulus of elasticity of recycled concrete gradually decreased as the rate of recycled aggregate substitution increased. In addition, the densification of recycled concrete was lower, while the workability of fresh concrete was affected by the high-water absorption of recycled aggregates in recycled concrete and became poorer (Lalla, 2014). These findings suggest some of the challenges that recycled concrete may face in engineering applications and provide an important reference for further optimization of recycled concrete formulations and processes. In 2001, Nisbet et al. summarized the total amount of construction waste generated annually in selected countries around the world, as well as the recycling rate of waste concrete. This study provides an overview of the global situation of construction waste disposal and reuse, and provides an important reference for us to understand the progress of construction waste management in various countries, as shown in Table 1.1 (Nisbet, Venta, & Foo, 2001).

Table 1.1

Total Amount of Construction Waste and Recycling Rate of Waste Concrete in Various Countries

Country	Construction waste (million tons)	Recycling rate of waste concrete / %
China	100	5
United States of America	136	50～57
EU 15 countries	180	28
Germany	59	17
Britain	30	45
France	24	15
Italy	20	9
Spain	13	<5
The Netherlands	11	90
Canada	11	42
Denmark	8	81
Belgium	7	87
Australia	5	41
Portugal	3	>5
Sweden	2	21
Greece	2	<5
Finland	1	41
Ireland	1	<5

According to the data in the table above, the United States, 15 European Union countries, China, and Germany are the countries that generate the highest total amount of construction waste per year. The Netherlands, Belgium, Denmark, and the United States, on the other hand, are some of the countries with the highest recycling rates for waste concrete. Apart from these countries, Japan is also known for its high recycling rate. These countries have carried out rapidly developing research and application of recycled concrete since the 1980s. They have made significant progress in the optimal grading of recycled concrete, the application range of recycled aggregates, and the basic mechanical properties of recycled concrete, and have applied these research results in actual projects to achieve resource recycling.

1.3.2 Current Trends and Developments of Recycled Concrete in China

Despite China's vast territory and abundant resources, many of which are non-renewable, the ecological problems caused by construction waste are receiving increasing attention as people become more aware of environmental protection. Research into the recycling of waste concrete began in China in the 1990s, and in October 1995, China passed “the Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution of the Environment”, which stipulates that waste-producing authorities must pay a waste disposal fee to be earmarked for environmental improvement. Also in 1997, the Ministry of Construction included "Comprehensive Utilization of Construction Waste Residues" in the key promotion projects for scientific and technological achievements of that year. These initiatives demonstrate the importance that the Chinese government attaches to construction waste disposal and resource utilization, and the positive efforts it has made to promote environmental protection and sustainable development. Since 1 November 2001, China has been implementing “the Urban Housing Demolition and Relocation Management Regulations”, which further improves the system of building demolition and construction waste treatment and recycling (Hu, Wu, & Shi, 2016).

In September 2014, the 4th National Academic Exchange Conference on Recycled Concrete was held at Beijing University of Technology, which focused on recycled concrete aggregate production, concrete material preparation, material properties, structural design and construction, and application of new technologies. This event promoted the research and development and engineering application of recycled concrete technology in China. The 5th National Academic Exchange Conference on Recycled Concrete was held in the ancient city of Xi'an from 16 to 18 December 2016. The conference explored topics such as recycled aggregate grading technology, structural design methods, economic management, and high-performance pathways through conference presentations, breakout group presentations, and technical tours. The conference conducted in-depth research on the innovation and development of recycled concrete and drew on the relevant achievements of experts at home and abroad to look forward to the future of China's construction waste resources. From 16 to 18 November 2018, Nanjing University of Aeronautics and Astronautics (NUAA) hosted the Sixth National Academic Exchange Conference on Recycled Concrete and the Second National Academic Exchange Conference on Construction Solid Waste. The conference focuses on the strategic needs of construction waste resourcing and environmentally friendly building materials during the "13th Five-Year Plan" period and carries out academic exchanges around the production of recycled concrete aggregates, material preparation, performance, structural design, and construction. The conference aims to improve the recycling and research level of recycled concrete and promote the development of construction waste recycling (Lang, Zhou, &Zhao, 2021).

Taiwan and Hong Kong, as two Special Administrative Regions of China, have also taken measures related to the recycling and reuse of construction waste. In 1999, Taiwan was hit by a major earthquake that resulted in a large amount of construction waste, and pilot sites for construction waste treatment stations were subsequently established. Through these pilot sites, 80% of the construction waste was successfully recycled, with 30% of the waste concrete being used for the construction of the road base. In 2002, the HKSAR Government also set up pilot construction waste treatment stations with a capacity of treating 2,400 tons of construction waste per day. The recycled aggregates produced by these treatment stations are widely used in mass concrete components of various types of buildings, such as pile-bearing platforms, floor tiles, beams, slabs, shear walls, retaining walls, and so on (Zhang, 2015).

Since entering the 21st century, Mainland China has also been gradually exploring the application of recycled concrete in building construction in 2003, Tongji University constructed a pavement built with recycled concrete in 2004, an eco-building demonstration building was built in Shanghai's Architecture Science and Technology Development Park, which used recycled concrete hollow-core masonry blocks for walls and achieved a recycled utilization rate of 60% of waste concrete in 2007, the Beijing Architectural Engineering Institute constructed a fully graded recycled concrete experimental building, which was the first building constructed with fully graded recycled concrete in China (Miao, 2015). Although the application of recycled concrete in China is in its initial stage, the application of recycled aggregates is not widespread. This situation is related to the fact that the government has not yet introduced relevant mandatory laws and regulations. However, with the increasing awareness of environmental protection, the application of recycled concrete in China's construction industry is still very promising and is expected to be further promoted and applied in the future.

In China, compared with the above countries, the application of waste concrete is still in the initial stage. The government attaches great importance to the recycling of waste concrete, encourages construction enterprises to increase the utilization of renewable resources, and formulates and revises relevant standards and norms, such as Technical Specification for Recycling of Waste Concrete and Technical Specification for Recycled Concrete Structures issued in 2016. In response to national policies, many cities in China have formulated corresponding local policies and codes to ensure that recycled concrete can be better used in projects. Waste concrete is used in paving roadbeds and pavement in Shanghai, recycled concrete hollow blocks are produced for non-load-bearing structures, and recycled concrete laboratory buildings are built in Beijing through different recycled concrete aggregate gradations (Wang, Wang, & Li, 2015).

Other domestic experts and scholars have also done a lot of positive work to improve the performance (physical properties, mechanical properties, structural properties) of recycled concrete through experiments and various measures. Southeast

University, Hua Zhong University of Science and Technology, Beijing Institute of Civil Engineering, Shenyang Institute of Civil Engineering, etc. have made gratifying achievements in the research and development of the technology of making sintered bricks and recycled concrete from municipal waste. After the disintegrated concrete and waste bricks are recycled, they can be used as concrete aggregates and lightweight aggregates to produce ordinary concrete or high-performance concrete blocks, and the strength of recycled concrete can reach C30 (Zhang, 2015).

Many scholars at home and abroad are doing research on the stress of recycled concrete, but the utilization of recycled concrete is not popular in China, and the utilization rate of recycled concrete is less than 20% at present. On the one hand, there are differences in the composition and performance of coarse and fine aggregate gradation, mix ratio, cement, and other materials of concrete; on the other hand, there are regional differences, which makes it impossible for China to directly use some foreign research results on recycled concrete. To better promote environmental protection and the reuse of resources in the construction industry, many scholars have made many contributions to the stress research of recycled concrete and put forward many valuable theoretical research results to promote the application of recycled concrete in practical projects. In China, the main reason is the defects of recycled concrete, so it is necessary to study the mechanical properties of recycled concrete and how to improve the mechanical properties of recycled concrete (Yang & Ye, 2020).

To effectively address the problem of construction waste, the Chinese government has set the goal of comprehensive utilization of construction waste in the “14th Five-Year” Plan and implemented a series of policy support and incentives. According to the Circular on “Leading Actions for Recycling Development” published on the website of China's National Development and Reform Commission in May 2017, the target of accelerating the resource utilization of construction waste was put forward. By 2020, the rate of resourceful treatment of municipal construction waste should reach 13% (Yan,2019). In July 2021, China's National Development and Reform Commission (NDRC) released the "14th Five-Year Plan for the Development of Circular Economy", which explicitly set out the targets by 2025: the efficiency of resource utilization will be significantly improved, the proportion of renewable resources replacing primary resources will be The efficiency of resource utilization will be greatly improved, the replacement ratio of renewable resources to primary resources will be further increased, and the role of the recycling economy in supporting and guaranteeing resource security will be further highlighted. In particular, the comprehensive utilization rate of construction waste is targeted to reach 60 %, to realize the concept of resource-saving and environmentally friendly development.

According to incomplete statistical data, about 30 production lines have been built in the country, whose annual capacity of processing construction waste exceeds 1 million tons. At the same time, there are also more than 30 production lines under construction with an annual capacity of more than 1 million tons of construction waste, while there are hundreds of small-scale processing enterprises. However, the total treatment capacity is still less than 100 million tons, and the domestic utilization rate of construction waste resources is only about 5%. At present, there are more than 100 enterprises with the ability to manufacture stationary construction waste resource utilization equipment, mainly producing equipment such as crushers and screening machines. In addition, there are 18 enterprises with the ability to manufacture mobile processing equipment. As for enterprises manufacturing equipment for recycled products from construction waste, including the production of products such as bricks and blocks, as well as mortar, concrete mixing plants, and inorganic materials, there are already more than 1,000 enterprises (Zhang, 2015).

At present, the application of domestic recycled aggregates is still in the preliminary stage, lack of systematic applied basic research, and there are some problems in technology. In terms of production, lack of source classification, disposal technology is relatively crude, lack of scientific and standardized production standards and quality control technology, fewer product varieties, and lower added value. In terms of energy saving and emission reduction, there is a lack of energy consumption control indicators, and most disposal enterprises are in a disorderly state. In terms of pollution prevention and control, mainly dust prevention, noise reduction, and pollutant emissions, only 30% of disposal enterprises above the 1 million tons level have better pollution prevention and control technology, some disposal enterprises need to be improved, and small enterprises may produce secondary pollution (Zhang, 2015).

At the same time, domestic research results show that recycled concrete and ordinary concrete in the raw materials, proportion, and construction technology, there are big differences, the current ordinary concrete standards, norms, etc. Do not apply to recycled concrete (Zhang, 2017). Although foreign research on recycled aggregates and recycled concrete is more in-depth and has achieved fruitful results, it is important to note that, due to the geographical characteristics of concrete, foreign research results only have a certain reference value, cannot be directly used to guide the practical application of recycled concrete in the project in China. In addition, due to the complexity of recycled aggregate itself and regional differences, even in various regions of the country, recycled aggregate may also have differences. Therefore, it is of great practical significance to carry out systematic research on recycled aggregates and recycled concrete in China.

1.4 Problem Statement

Extreme weather events are occurring more frequently around the world today, with the greenhouse effect being one of the main causes, according to statistics, global carbon dioxide emissions are approximately 30 billion tons per year, accounting for 74% of greenhouse gas emissions (Huang, Wang, & Fang, 2019). In response to the global warming effects caused by the greenhouse effect, countries are actively implementing measures to address the issue. Producing 1 ton of recycled concrete can effectively reduce CO_2 emissions by 23~28%, decrease the extraction of natural aggregates, and save 10~20% in material costs (Zhang,2015). Research reports indicate that in 2021, China's construction waste amounted to approximately 3.2 billion tons, and by 2026, the amount of construction waste is expected to exceed 4 billion tons (Huang, Wang, & Fang,2020). Faced with the increasing amount of construction waste and the contradiction of protecting the natural environment, recycling recycled coarse aggregate responds to the national policy. Under the current policy of highly demanding environmental protection, man and nature should develop harmoniously. The popularization and application of recycled concrete are of great significance in saving resources and healthy and sustainable development of the concrete industry, it can promote the stable and healthy development of the country.

The recycling of waste concrete has become one of the important pathways for sustainable development in the construction industry. After the recycled concrete coarse aggregate is crushed, its surface is wrapped with the original mortar, which leads to its rough surface, more water chestnut, high-water absorption, Low apparent density, micro-cracks in the interior, and high crushability (Wu et al., 2022), affecting the durability and overall stability of recycled concrete. Due to the inherent defects of recycled concrete, although China generates nearly 3 billion tons of construction waste annually, the utilization rate of waste concrete is less than 5% (Li, 2019). To address this issue, current research findings are being explored to discuss how to improve the performance of recycled concrete to meet engineering requirements. Firstly, improving the physical properties of recycled coarse aggregates and enhancing their density is essential, the addition of steel fibers can improve the strength of the concrete, enhance its toughness, and increase crack resistance. Therefore, combining reinforced recycled coarse aggregates with steel fibers can effectively improve the overall mechanical performance of recycled concrete and achieve efficient resource utilization.

1.5 Research Problem

Currently, research on the mechanical properties of recycled concrete produced by incorporating steel fibers into reinforced recycled coarse aggregates is limited, there is a lack of systematic experimental data and theoretical analysis on the mechanical properties of reinforced recycled coarse aggregates with different types of steel fiber incorporation. Therefore, this thesis aims to explore the following aspects:

- i How does reinforcing recycled coarse aggregates improve their physical properties, and what are the underlying mechanisms?
- ii What are the effects of steel fiber incorporation on the mechanical and toughness properties of recycled concrete? What is the optimal volume fraction of steel fibers to be added?
- iii How does the combined reinforcement effect of reinforced recycled coarse aggregates and steel fiber incorporation influence the stress damage behavior?

1.6 Research Objectives

It provides some research information for promoting the recycling of recycled coarse aggregate in engineering, reducing the discharge of construction waste, realizing low carbonization, and protecting the environment. Recycled coarse aggregates have defects such as high-water absorption and microcracks, high water absorption could affect concrete durability, while micro-cracks could weaken structural integrity. How to reduce the defects of the recycled coarse aggregate itself and strengthen the mechanical properties of recycled coarse aggregate. Reinforcement of recycled coarse aggregates is considered in terms of improving the densification of coarse aggregates, the methods to improve the compactness of coarse aggregates include volcanic ash slurry immersion, carbon dioxide reinforcement, nanomaterials modification, and cementitious materials adherence (Wang, Zheng, &You, 2021). Good coarse aggregate gradation can effectively improve the compactness of recycled concrete. In this study, the grading and cement slurry reinforcement method, which is simple to operate and less costly, was selected for the reinforcement of recycled coarse aggregate to increase the compactness of the recycled coarse aggregate. Improvement of the tensile, shear, and cracking resistance of recycled concrete through the incorporation of steel fibers, thus improving the toughness and ductility of recycled concrete.

i To study that recycled coarse aggregate can effectively improve the mechanical properties of recycled concrete after grading optimization and cement slurry reinforcement.

ii To study the addition of steel fibers in recycled concrete as an effective method to enhance its mechanical properties.

iii Exploring the enhancement of recycled coarse aggregates and the addition of steel fibers as effective approaches to reduce stress-induced damage in recycled concrete.

1.7 Scope of Research

Select properly graded recycled coarse aggregates and determine their corresponding physical properties, such as water absorption and crushability index, etc. Use cement slurry reinforcement treatment and incorporate steel fibers with good mechanical performance to conduct analysis of the mechanical properties and stress damage. This experiment use a microcomputer control electro-hydraulic servo material testing machine, design three groups of test conditions for comparative analysis, the specific program as follows：I Natural concrete block (experimental control group); II Recycled concrete group (normal recycled coarse aggregate, 100 % replacement, experimental control group)； III Recycled concrete reinforcement group (recycled coarse aggregate strengthening,100% replacement).

Different groups of concrete were spiked with steel fiber with the amount of steel fiber at volume rates of 0, 1%, 2%, and 3% respectively. Compression, split tensile, shear, and biaxial compression shear mechanical tests and force damage studies of steel fiber recycled concrete uniaxially were carried out. Scope of research:

i Since concrete-like materials are composite materials, their mechanical properties are affected by a variety of factors. For steel fiber recycled concrete, the factors affecting its mechanical properties are the substitution rate of recycled coarse aggregate, the characteristics of the recycled coarse aggregate, the water-cement ratio, the amount of steel fiber admixture, and the size of the specimen. Comprehensive analysis to determine the substitution rate of recycled coarse aggregate, the method of reinforcing recycled coarse aggregate, the mix ratio, the volumetric rate of steel fiber and the size of the specimen, etc.

ii Carry out uniaxial compression, split tensile, shear and biaxial compression, and shear mechanical tests on steel fiber recycled concrete specimens using a microcomputer-controlled electro-hydraulic servo material testing machine to obtain test data and provide a database for the subsequent analysis.

iii To study the mechanical properties of steel fiber recycled concrete specimens with different concrete coarse aggregates and different steel fiber admixtures, analysis of the change law of mechanical properties, stress-strain relationship, analysis of the peak stress, peak strain, and damage pattern, make a comparison and summary, explore the mechanical properties of recycled concrete.

iv Using the DIC technique to measure the displacement and strain fields, the apparent damage analysis of steel fiber recycled concrete specimens was carried out, investigating the effect of reinforcement of recycled coarse aggregate and incorporation of steel fiber on the stress damage of recycled concrete.

Statistically analyze the experimental data to study the comprehensive effects of three types of coarse aggregates and steel fiber incorporation on the mechanical properties of concrete, perform mathematical modeling to explore the relationship between the mechanical properties of recycled concrete and the material mix parameters. Compare and analyze the differences in mechanical properties and deformation behavior between recycled coarse aggregate concrete and ordinary concrete, and summarize the optimal volume fraction of steel fibers for reinforcing recycled concrete. Based on the experimental results, evaluate the feasibility of applying reinforced recycled coarse aggregates and steel fiber reinforcement technologies in engineering.

1.8 Research Hypothesis

Reduce the pre-existing microcracks in recycled aggregates, lower the water absorption rate, and enhance the density to improve the mechanical properties of recycled concrete. The reinforced recycled coarse aggregate is added with steel fiber to improve the mechanical properties of concrete, through comparative analysis of the test and data, to investigate the mechanism of steel fiber admixture in recycled concrete on the damage of recycled concrete, and the effect of steel fiber admixture on the cracking resistance of recycled concrete. The specific research hypotheses are as follows：

H1: The better the chemical reinforcement of recycled aggregate, the less the microcracks of recycled aggregate.

H2: The better the chemical reinforcement of recycled coarse aggregate, the smaller the water absorption of recycled aggregate.

H3: The less microcracks and water absorption of recycled aggregate, the closer the mechanical properties of recycled concrete are to those of ordinary concrete.

H4: In a certain range, the more steel fiber added, the better the compressive performance of recycled concrete.

H5: In a certain range, the more steel fiber added, the better the shear performance of recycled concrete.

H6: In a certain range, the more steel fiber added, the better the tensile performance of recycled concrete.

H7: In a certain range, the higher the steel fiber incorporation, the better the biaxial compression-shear performance of recycled concrete.

H8: Within a certain range, the higher the steel fiber admixture, the less stress damage the recycled concrete will suffer.

H9: In a certain range, the more steel fiber incorporated, the better the cracking resistance of the recycled concrete.

H10: The better the crack resistance, force damage, compressive properties, tensile properties, shear properties, and biaxial compression-shear stress properties of recycled concrete, the closer the mechanical properties are to those of ordinary concrete.

1.9 Research Framework

1.9.1 Reinforcement of Regenerated Coarse Aggregate

The strength of recycled aggregate is lower than that of natural aggregate, and its surface is rough. Enhancing the interlocking ability of the recycled aggregate interface can improve its performance to some extent. The surface of recycled aggregate is coated with a significant amount of mortar, resulting in lower bulk density and apparent density, while the crushing index and water absorption are higher. Consequently, this reduces the compressive strength and workability of recycled aggregate concrete (Zhang,2017).

If effective methods to enhance recycled aggregates and recycled concrete can be found, the performance of recycled aggregate concrete can be fundamentally improved. Therefore, research on strengthening recycled aggregates and recycled concrete is highly valuable. Reinforced with mineral admixtures or polymer impregnation, filling of cracks, voids, etc. in coarse aggregates by means of fine particle slurry, improvement of densification of recycled coarse aggregates (Feng et al., 2022).

Preferred recycled coarse aggregate gradation, cement slurry reinforced recycled coarse aggregate. Corresponds to the following assumptions, H1: The better the chemical strengthening of recycled aggregate, the less the microcracks of recycled aggregate. H2: The better the chemical strengthening of recycled coarse aggregate, the smaller the water absorption of recycled aggregate. H3: The less microcracks and water absorption of recycled aggregate, the closer the mechanical properties of recycled concrete are to those of ordinary concrete.

1.9.2 Incorporation of Steel Fiber

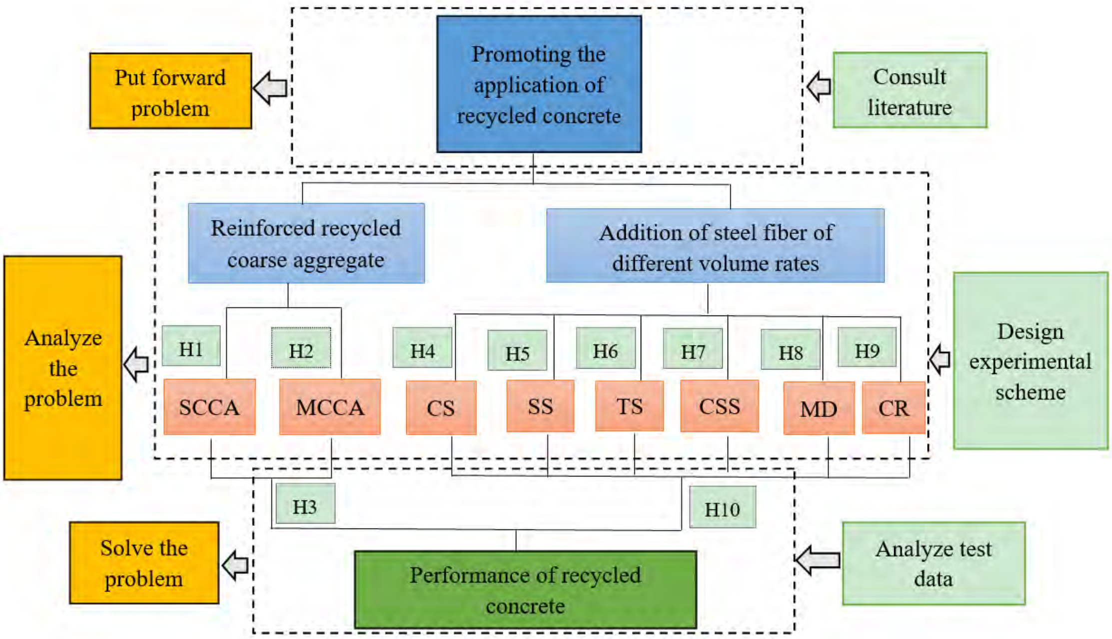
Due to its advantages of high strength, good toughness, and easy construction, steel fiber forms a new type of composite material with recycled concrete, which can well improve the mechanical properties of recycled concrete such as tensile, shear, and flexural, delay the cracking of concrete, and improve the application performance of recycled concrete (Ye, Wang, &Xie, 2021; Hai, Liu, &Yang, 2021). Scholars in many countries increase various fibers to improve the performance of recycled concrete (Zhu, Han, &Zhang, 2020; Huang, Zhao, &Wang, 2021) and obtained certain research results. H4：In a certain range, the more steel fiber added, the better the compressive performance of recycled concrete. H5: In a certain range, the more steel fiber added, the better the shear performance of recycled concrete. H6: In a certain range, the more steel fiber added, the better the tensile performance of recycled concrete. H7: In a certain range, the higher the steel fiber incorporation, the better the biaxial compression-shear performance of recycled concrete.

The reason for the damage to the member is that the displacement exceeds the permissible value, using a non-contact optical measurement technique - Digital Image Correlation (DIC), a non-contact optical measurement technique, can accurately measure the displacement and strain of the specimen during the stressing process, and accurately analyze the stress damage state of the steel fiber recycled concrete specimen. H8: Within a certain range, the higher the steel fiber admixture, the less stress damage the recycled concrete will suffer. H9: In a certain range, the more steel fiber incorporated, the better the cracking resistance of the recycled concrete. H10: The better the crack resistance, force damage, compressive properties, tensile properties, shear properties, and biaxial compression-shear stress properties of recycled concrete, the closer the mechanical properties are to those of ordinary concrete.

In this thesis, ordinary concrete, recycled concrete (non-reinforced), and recycled concrete reinforced with recycled coarse aggregates, the replacement rate of recycled coarse aggregates is 100% and incorporating different steel fiber volume fractions, to study the damage mechanism of steel fiber recycled concrete in uniaxial and biaxial stress states under different working conditions, to obtain the test data, the specimens were tested by a microcomputer-controlled electro-hydraulic servo material testing machine, get the change curves of the load-displacement process of steel fiber concrete and steel fiber recycled concrete in compression, tension, shear and compression-shear, and to analysis the influence of different change parameters on the peak stress, compressive strength, tensile strength and shear strength of steel fiber concrete and steel fiber recycled concrete. With the help of the digital image correlation (DIC) method, the force damage of concrete specimens under different working conditions was measured in an all-round, efficient, and accurate way, and the effects of recycled coarse aggregate reinforcement and steel fiber mixing on the force damage of the specimens were comparatively analysis. The framework of the study Figure. 1.3.

Figure 1.3

Research Frame Diagram



Note, SCCA= Surface Cracks in Coarse Aggregates; MCCA= Moisture Content of Coarse Aggregates; CS = Compressive Strength; SS = Shear Strength; TS = Tensile strength; CSS = Compressive Shear Strength; MD= Mechanical Damage; CR= Crack Resistance.

The specific studies are as follows:

i Research on the source of recycled coarse aggregate, production and processing technology, and the reinforcement method of recycled aggregate. Combined with the relevant literature, design a suitable recycled coarse aggregate grading reinforcement method, and based on grading reinforcement, design a cement slurry reinforcement method, through which the porosity and water absorption of recycled coarse aggregate can be reduced, the apparent density and bulk density can be increased, and the crushing index can be reduced. Compare and contrast the basic properties of recycled coarse aggregate and natural coarse aggregate, and investigate the influence of the basic properties of recycled coarse aggregate on the performance of recycled concrete.

ii Ordinary coarse aggregate, non-reinforced recycled coarse aggregate, and reinforced recycled coarse aggregate were selected to make concrete with a strength class of C30, and the effects of the flow and mechanical properties of recycled coarse aggregate concrete were investigated at different substitution rates (0, 100%).

iii To maximize the use of recycled coarse aggregate, the non-reinforced and reinforced recycled coarse aggregate replaced 100% of the natural coarse aggregate, participated in different amounts of steel fiber (0, 1%, 2%, 3%), the formation of steel fiber recycled concrete, the study of the flow and mechanical properties of the steel fiber recycled concrete, to explore and analysis the destruction mechanism of steel fiber recycled concrete.

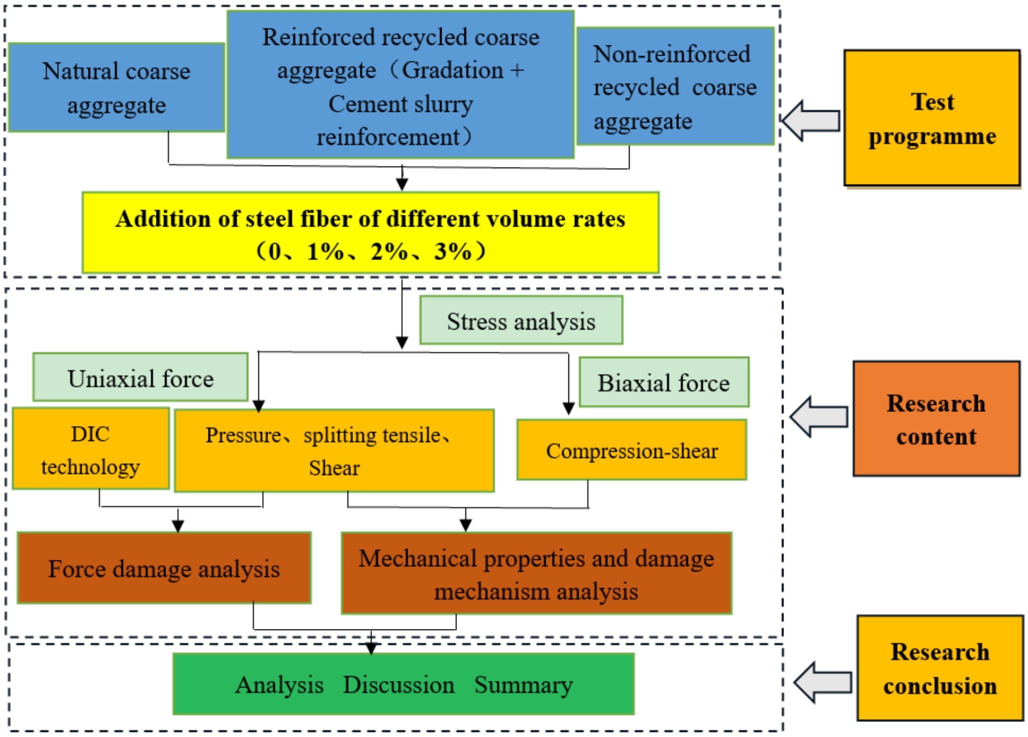
iv Conduct uniaxial compressive, tensile, and shear tests and biaxial compression-shear tests on each group of specimens, analyze the load-displacement graphs of the tests, and analyze the mechanical properties of reinforced recycled concrete.

v Adopting modern digital image correlation (DIC) optical measurement technology, we can measure the force damage of concrete specimens under different working conditions in an all-round, efficient, and accurate way, and compare and analyze the effects of recycled coarse aggregate reinforcement and steel fiber mixing on the force damage of specimens.

The research technology roadmap Figure1.4.

Figure 1.4

Technology Roadmap



1.9.3 Limitations of The Study

There are performance differences between recycled coarse aggregates and natural coarse aggregates. Enhancing the coarse aggregates or adding fibers to the recycled coarse aggregates can be considered to improve their performance. Due to the inherent drawbacks of recycled coarse aggregates, their mechanical properties and durability are lower compared to natural aggregates (Wang, 2022). Although many scholars at home and abroad have conducted extensive research on the enhancement of recycled coarse aggregates, some methods are overly complex, and the design calculations are cumbersome, making them difficult to promote and apply. There are still some issues with the basic mechanical properties of recycled concrete, which limit its application range. In European and American countries, recycled aggregate concrete is primarily used in non-structural concrete and road construction. Additionally, the replacement rate of recycled coarse aggregates is typically below 50%, significantly restricting their application scope and the commercialization of recycled concrete production. Lastly, adding steel fibers to recycled coarse aggregates is an effective method to improve the performance of recycled concrete. However, research on the uniaxial and biaxial stress-deformation behavior of steel fiber-reinforced recycled concrete under compression, tension, and shear is still incomplete. The mechanisms of crack development and failure remain underexplored. Therefore, it is necessary to study the mechanical properties of steel fiber-reinforced recycled concrete.