Exploring the Current Research Status of High-Performance Materials in the Strengthening of Existing Bridges

Chengjun Yu*

College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, Heilongjiang Province, 150001, China

*Corresponding author: ycjun@hrbeu.edu.cn

Abstract. The bridge industry in China began in the 1950s and rapidly developed in the 1980s, with a large number of reinforced concrete bridges being built and put into use. However, with the rapid growth of the national economy and the vigorous development of transportation, the total volume of transportation has surged in recent years, and the axle load of vehicles has continuously increased. This has led to many existing bridges being in a state of overload for a long time, resulting in aging or even damage, which seriously affects the smooth flow of traffic. Traditional bridge reinforcement methods, due to their poor durability, long construction periods, and impact on traffic, have gradually shown lag and inadaptability. This paper focuses on the application of high-performance materials in bridge reinforcement, mainly exploring the technical characteristics, design schemes, and reinforcement effects of ultra-high toughness resin concrete, ultra-high performance concrete, and carbon fiber materials. Research indicates that these materials can significantly enhance the load-bearing capacity, durability, and construction efficiency of bridges, providing a reliable solution for the long life and high performance of bridges. This study offers new insights into the field of bridge reinforcement and is of great significance for the sustainable development of transportation infrastructure.

Keywords: Bridge Strengthening; High-Performance Materials; Ultra-High Toughness Resin Concrete; Ultra-High Performance Concrete; Carbon Fiber.

1. Introduction

In the construction of modern transportation systems, bridges are crucial infrastructure components. Bridge materials have limited lifespans and are susceptible to corrosion and fatigue. Before reaching their service life, they may exhibit defects such as component damage and plastic deformation, leading to a decrease in local strength. To address the issue of reduced local strength in bridges, appropriate reinforcement measures must be taken.

Traditional bridge reinforcement methods have several drawbacks, including long construction periods, large operational spaces required, high costs, and insufficient durability. These issues can significantly reduce traffic efficiency[1]· Moreover, poor durability necessitates repeated adjustments to overcome material corrosion, which can reduce the lifespan of bridges. During the repair process, the overall integrity, load-bearing mode, and elastic deformation capacity of the bridge may be compromised, negatively affecting its dynamic characteristics, functionality, and aesthetics. Additionally, the insufficient strength of traditional materials can lead to safety hazards. In summary, traditional reinforcement materials and methods have shown signs of lag and inadaptability.

The introduction of high-performance materials has injected new vitality into bridge reinforcement technology. For instance, ultra-high toughness resin concrete and carbon fiber composite materials not only excel in strength and durability but also effectively optimize the construction process, significantly improving the efficiency of the project. These innovative materials, with their outstanding physical properties and diverse design advantages, offer irreplaceable superiority compared to traditional materials and have gradually become the preferred solution for bridge structure reinforcement and extending service life.

This paper focuses on the practical application of high-performance materials in bridge reinforcement, covering the analysis of the characteristics of ultra-high toughness resin concrete and carbon fiber composite materials, research on design schemes, and a comparative discussion with traditional reinforcement materials. Through in-depth and systematic research, the aim is to provide scientific evidence and practical references for the optimization of bridge structure reinforcement and long-term durability.

2. Ultra-high Strength and Toughness Resin Concrete

2.1. Introduction to the material

Super-strong tough resin concrete is a type of epoxy grouting material that has been used in recent years. Compared to the brittle characteristics and insufficient environmental durability of traditional materials, this material can be used in environments with higher precision requirements and greater load demands. Therefore, it is often applied in load transfer, corrosion protection, rock consolidation, and many other aspects. It also plays an important role in enhancing the overall performance of existing bridge reinforcement projects.

2.1.2 Material design

The mix design of super-strong high toughness resin concrete directly affects its durability, strength, and various construction properties. The mix design of the material needs to be continuously optimized through experiments to ensure that its strength, durability, and construction properties meet actual requirements. Only after verifying various indicators can the final mix be determined. Super-strong toughness resin concrete primarily consists of polyether, polyisocyanate, and fly ash. Studies have shown that increasing the proportion of fly ash significantly reduces costs, but at the same time, it leads to a decrease in material fluidity, making construction processes such as pumping more difficult[2].

When the mix design is scientific, the super-strong tough resin concrete is lightweight and exhibits excellent physical properties. It can effectively reduce the burden on structures, enhance overall crack resistance and flexural performance, and extend service life[3]. Moreover, it maintains good fluidity, eliminating the need for complex equipment and construction techniques. It is easy to operate, ensuring construction quality and speed. This improves construction safety and enhances the reliability of bridge reinforcement.

According to T/CCPA 7—2018 "Basic Properties and Test Methods of Ultra-High Performance Concrete," compressive strength tests are conducted on ultra-high toughness resin concrete.

2.2. Material Features and Benefits

Super-strong tough resin concrete has many excellent properties and can be fully applied in bridge reinforcement projects. When damage to concrete components in existing bridge projects is detected, this material can be used to wrap or fill the structural parts that do not meet the strength requirements, so that the strength of the reinforced components reaches the desired level[4]. The excellent properties include the following points:

(1) Superior tensile and torsional performance. This material can fully transmit existing loads to beam components, thereby significantly enhancing the load-bearing capacity, effectively reducing the risk of crack formation, and further significantly improving the adhesion of the beam body.

(2) Excellent stability. Under normal circumstances, concrete materials become more brittle and their mechanical properties decrease under low-temperature conditions, making them prone to cracking. In high-temperature situations, they are susceptible to material expansion. However, super-strong high toughness resin concrete can maintain its structural performance in both high and low-temperature environments, meeting the load transfer requirements.

(3) High elastic modulus. This material has a strong ability to resist deformation, with minimal deformation, allowing it to withstand significant pressure and maintain the stability and safety of the structure.

(4) Good fluidity. During construction, this material is easy to flow and pump, allowing it to smoothly fill gaps in molds or structures, closely integrate with them, and form an integrated load-bearing system.

(5) Strong corrosion resistance. Super-strong high toughness concrete can effectively resist the erosion of environmental factors, reducing the frequency of maintenance and thus lowering maintenance costs.

(6) High early strength. After construction, this material can quickly achieve a high level of strength, ensuring that the structure has sufficient load-bearing capacity in a short time, allowing it to be put into use early, reducing pressure on other roads, and having minimal impact on traffic efficiency.

(7) Pre-packaged. This ensures consistent performance of each batch of material, reducing performance fluctuations caused by different batches or mixing errors, and improving the reliability of the material[5].

2.3. Usually Reinforcement Schemes

Based on the analysis and calculation results of the force on concrete components, combined with their force characteristics, MPC super-strong high toughness resin concrete can be applied to wrap the corresponding positions of concrete components that do not meet the strength requirements, thereby enhancing their strength to meet the load-bearing requirements.

2.3.1 Reinforcement Scheme Design

According to the standard T/CCPA 7—2018 "Basic Properties and Test Methods of Ultra-High Performance Concrete," rectangular prism specimens of super-strong high toughness resin concrete were analyzed through orthogonal testing, focusing on compressive strength, compressive deformation force, and elastic modulus. Based on the results of the orthogonal tests, the optimal mix ratio for super-strong high toughness resin concrete was determined to be polyether: polyisocyanate: fly ash = 1.0:1.0:3.8[6].

Based on relevant specifications and materials, combined with the types of bridge diseases and historical maintenance records, a general reinforcement plan involves using external wrapping of super-strong high toughness resin concrete and prestress analysis to locally reinforce bridges. The specific construction plan involves casting a composite material that is 28cm wide and 5cm thick at the bottom of the T-beam flange. Additionally, high-strength, low-relaxation prestressed steel strands are installed near the bottom edge of the reinforcement material to serve as longitudinal prestressed steel bundles.

2.3.2 Reinforcement Implementation Technology

To ensure the smooth progress of the local reinforcement project, the construction process should be carried out in the following steps: cleaning the surface of the main beam, locating and drilling holes for reinforcement bars, installing fixtures, threading and positioning the prestressed steel bundles and their positioning devices, prestressing the steel, erecting formwork, pouring the super-strong high toughness resin concrete, and finally demolding[7].

(1) Surface cleaning of the main beam. The beam body is roughened using manual labor and small tools. During construction, it is necessary to remove the loose parts of the concrete to enhance the adhesion of the super-strong high toughness resin material. After roughening, the surface of the structure must be cleaned thoroughly with an ultra-high-pressure water gun to prevent any contamination that could affect the material's performance.

(2) Component and formwork installation. During installation, the components are first positioned and laid out, and then the reinforcement mesh is installed from one end to the other. Considering the structural dimensions of the beam reinforcement and the special adhesion of the super-strong high toughness resin material, the formwork is preferably made on-site using wooden molds. The stability of the formwork structure is controlled according to its structural dimensions, and polyester board material is attached to the surface of the formwork to facilitate subsequent demolding and improve

construction efficiency. When installing the formwork, it is essential to ensure that the structure is properly sealed to prevent leakage of the concrete.

(3) Pouring of composite material. The composite material is introduced into the formwork using a high-position funnel, utilizing its self-leveling properties to fill slowly. The high-position funnel is suitable for pouring heights of 2 to 5 meters; for heights exceeding 5 meters, additional conduits or layered operations are required, with each layer not exceeding 50cm in thickness to prevent segregation or layering. The material's fluidity should meet the requirements of a slump of 180mm to 220mm or an expansion of 500mm to 600mm, and the performance should be adjusted according to the site conditions.

After pouring, a comprehensive inspection is necessary to prevent incomplete filling or the formation of voids. Inspection methods include visually checking for unfilled areas at the openings and edges of the formwork, tapping the surface to listen for solid or hollow sounds, using a probe to measure depth, and employing ultrasonic detection to check for internal voids or layering. The filling should be gap-free, without settlement, and smoothly transition at the edges. If defects are found, they should be repaired using low-pressure grouting. During construction, the flow rate from the funnel outlet should be controlled to prevent segregation caused by impact; in extreme temperature environments, insulation or cooling measures should be taken to ensure the material's performance.

Ultra-high toughness resin concrete has self-curing characteristics, and no curing is required after pouring.

(4) Demolding and cleaning. The demolding time should be scheduled according to the construction progress, and it is recommended to do it the next day. After demolding, the cured material will have the original polyester film adhered to it. Since this film is thin and transparent, no special treatment is required.

3. Ultra-High Performance Concrete Reinforcement

With the continuous advancement of Ultra-High Performance Concrete (UHPC) material preparation technologies and the ongoing refinement of construction techniques, the application of UHPC in bridge reinforcement is becoming increasingly widespread. By combining UHPC with traditional concrete or steel structures, new types of bridge structural forms, such as UHPC-encased steel box concrete composite structures, can be developed.

3.1. Preparation process

The preparation process of UHPC includes four key steps: material selection, mixing and stirring, molding, and curing. In material selection, it is necessary to choose high-strength cement, highly reactive mineral admixtures, and high-quality fine aggregates. Fine aggregates help improve the fluidity and uniformity of the concrete. Additionally, high-performance water reducers and fiber reinforcement agents are added as needed. The amount of water used is 15% to 30% of the cement mass to ensure good workability [8].

During the mixing and stirring stage, after the solid components are thoroughly mixed, the liquid components are gradually added and stirred until uniform, avoiding the formation of bubbles and layering. When molding, the formwork must be pre-treated to prevent adhesion. After molding, wet curing (for more than 7 days) or high-temperature steam curing is used to enhance early strength and material density.

3.2. Material Features and Benefits

UHPC exhibits significant tensile strain hardening behavior, which effectively resists the formation and propagation of cracks, thereby enhancing the overall performance and service life of structural components. In terms of durability, the micro-pore structure of UHPC significantly reduces the likelihood of intrusion by water, gases, and chlorides, giving it excellent resistance in corrosive environments. In addition, UHPC has very good fluidity, which allows it to easily fill complex structures, improving construction efficiency and ensuring construction quality. The high elastic modulus and low shrinkage rate of UHPC further enhance its ability to control deformation, enabling it to maintain stability under high loads. These characteristics endow UHPC with outstanding comprehensive performance, making it an ideal choice for enhancing the durability of bridge structures and extending their service life.

3.3. Contrast with Cement Concrete

Compared to traditional cement concrete, UHPC has significant advantages in mechanical properties, durability, and construction performance.

In terms of mechanical properties, the compressive and tensile strengths of UHPC are much higher than those of ordinary cement concrete. For instance, the compressive strength of ordinary cement concrete is typically around 20 MPa, while UHPC can exceed 200 MPa[9]. Moreover, the tensile strain hardening behavior of UHPC significantly enhances its crack resistance, whereas ordinary concrete usually exhibits brittle fracture.

Regarding durability, the micro-pore structure and high density of UHPC greatly improve its resistance to corrosive media compared to ordinary concrete. For example, studies have shown that the chloride ion diffusion coefficient of UHPC can be as low as 10^-13 m^2/s, which is 2 to 3 orders of magnitude lower than that of ordinary concrete, thus significantly reducing the risk of steel reinforcement corrosion[10].

In terms of construction performance, the excellent fluidity and self-compacting properties of UHPC make it suitable for the construction of complex structures, reducing the need for vibration equipment and improving construction efficiency[11]. Although the initial material cost of UHPC is higher, its superior comprehensive performance results in significantly better cost-effectiveness over its entire service life compared to traditional cement concrete.

4. Application of Carbon Fiber Materials

Carbon fiber is a high-strength fiber material composed of carbon with a content exceeding 90%. Its excellent properties and wide range of applications have made it highly favored in modern engineering. In the field of bridge reinforcement, carbon fiber materials have become an important choice to address the deficiencies of traditional reinforcement materials due to their high strength, low mass, corrosion resistance, and good plasticity.

4.1. Introduction to the Material and the Principles That Can Be Applied

Carbon fiber is a high-strength fiber material produced from organic polymers such as polyacrylonitrile (PAN) and pitches through processes of high-temperature oxidation, carbonization, and graphitization. Its microstructure is quasi-crystalline carbon. The high strength of carbon fiber originates from the covalent bond structure of its carbon atoms, which provides an extremely strong and stable structure, allowing carbon fiber to achieve a tensile strength of over 3000 MPa.

In bridge reinforcement, carbon fiber materials are primarily used in the form of fiber sheets, fiber plates, and fiber rods. They are combined with the surface of concrete or steel through adhesives such as epoxy resin to form a composite material layer. This composite layer shares the load with the underlying structure, redistributing the load to the carbon fiber, thereby reducing stress concentration in the original structure and enhancing the overall load-bearing capacity and stability of the structure.

4.2. Material Advantages

The advantages of carbon fiber materials are mainly reflected in the following aspects:

(1) Efficient Reinforcement: Carbon fiber composite materials have much higher strength and stiffness than traditional steel and concrete due to their unique molecular structure[12]. This allows them to effectively transmit and distribute loads when bridges are subjected to forces, thereby

maintaining the stability of the bridge, reducing the risk of deformation, and enhancing the overall performance of the structure.

(2) Lightweight Characteristics: The density of carbon fiber composite materials is only 1/4 that of steel and 1/5 that of concrete, significantly reducing the self-weight of bridge structures[13]. Without increasing the self-weight of the bridge, carbon fiber can greatly enhance the load-bearing capacity of the structure, reducing the requirements for the foundation.

(3) Construction Convenience: Carbon fiber composite materials have good construction adaptability, making them suitable for various complex structural shapes of bridges. The construction process does not require large equipment or complex techniques. The low spatial requirements for construction greatly reduce time and labor costs, improving engineering efficiency.

4.3. The Basic Process of Material Use

When reinforcing bridges with carbon fiber composite materials, it is essential to follow a standardized construction process. Before construction, it is necessary to clarify the reinforcement needs of the bridge, develop a reasonable construction plan, and prepare materials and tools such as carbon fiber fabric, adhesive, and cutting equipment. Next, the surface of the bridge should be treated, including positioning and marking to ensure the accuracy of the adhesive location, removing surface dust and impurities, grinding and repairing the substrate to eliminate dust, impurities, and cracks that may affect the adhesion of the adhesive, and chamfering the corners with a minimum radius of 20 mm to enhance the adhesive effect and prevent damage to the carbon fiber due to excessive bending during application, ensuring that the composite material is evenly loaded. After completing the surface treatment, apply a primer, using a roller to evenly apply the well-mixed and filtered primer onto the bridge surface with a thickness of 2 to 3 mm, ensuring that the primer fully penetrates the substrate and reaches a dry state[14].

Following this, cut the carbon fiber fabric according to the design requirements and apply it to the bridge surface. The longitudinal joint overlap length should be greater than 10 cm, and a roller should be used to compact it, avoiding the formation of bubbles and voids, and ensuring that the carbon fiber fabric is closely bonded to the bridge surface.

4.4. Follow-up Maintenance

Curing and maintenance is a critical step in the reinforcement of bridges with carbon fiber composite materials, typically requiring 24 to 48 hours[15]. After the application is complete, it is essential to ensure that the material is not contaminated by dust and impurities during the curing process, to avoid direct sunlight and violent vibrations of the bridge, and to maintain suitable environmental conditions with a relative humidity controlled between 40% and 60%. Once the curing is complete, a quality inspection of the reinforced area is necessary. This can be done by tapping the applied area with a hammer; if the sound is crisp and the touch is hard, it indicates a good adhesion effect. Alternatively, an ultrasonic detector can be used for inspection; if the signal is stable and shows no abnormalities, it confirms that the reinforcement quality meets the standards.

5. Suggestion

In bridge reinforcement projects, traditional materials and technologies face numerous challenges. Ordinary concrete and steel are prone to performance degradation under high loads, corrosive environments, and extreme temperatures, making it difficult to meet the requirements for the service life and safety of bridges. However, traditional reinforcement materials are typically heavy, complex to construct, and highly dependent on construction sites and equipment, limiting their application in confined spaces or complex structures. To address these issues, there is an urgent need to develop and apply innovative materials with high strength, durability, and construction flexibility.

Super-strong high toughness resin concrete performs exceptionally in compressive and tensile strength, making it suitable for the reinforcement of medium and low-strength bridges, especially maintaining stable performance under extreme temperature conditions. Ultra-High Performance Concrete (UHPC) stands out in corrosive environments and high load conditions due to its compressive strength exceeding 200 MPa and excellent durability. Its dense microstructure significantly improves permeability resistance, extending the life of bridges. Carbon fiber composite materials have extremely high tensile strength, over 3000 MPa, significantly enhancing the structure's bending and shear resistance, and their corrosion resistance is outstanding, making them ideal for long-term bridge reinforcement.

The construction process of super-strong high toughness resin concrete is simple, with good fluidity, easy pouring, and self-curing characteristics that shorten construction time and make operations convenient. Although UHPC has higher construction requirements, its good fluidity and self-compacting properties reduce the difficulty. Carbon fiber composite materials are flexible in construction, do not require large equipment, and are particularly suitable for reinforcing complex structures or confined spaces. Carbon fiber sheets are lightweight and easy to cut, meeting diverse design needs.

Super-strong high toughness resin concrete is suitable for medium and low strength reinforcement, enhancing crack resistance and load-bearing capacity, and its corrosion resistance makes it an ideal reinforcement material for aging or damaged structures. UHPC has significant advantages in high strength requirements and extreme environments, making it the preferred choice for high-performance bridge reinforcement. Carbon fiber composite materials, due to their flexibility, are suitable for rapid repairs and local reinforcements, especially in complex structures such as bridges and tunnels, and are a reliable choice for high-demand reinforcement projects.

Future bridge reinforcement will rely on advancements in material science and construction technology, enhancing the multifunctionality of materials, construction efficiency, and cost-effectiveness. Super-strong high toughness resin concrete, UHPC, and carbon fiber composite materials will be widely applied. Innovative materials such as carbon fiber-UHPC composite technology and environmentally friendly high-performance resins will provide more solutions. Intelligent technologies will promote bridge health monitoring and maintenance, achieving full lifecycle management and optimization.

6. Conclusion

This paper systematically studies the application of super-strong high toughness resin concrete, ultra-high performance concrete, and carbon fiber composite materials in the field of bridge reinforcement. It uses comparative analysis to comprehensively evaluate these three high-performance materials from multiple perspectives, including material properties, construction techniques, and applicable scenarios and verifies their actual performance in bridge reinforcement through practical engineering cases. The study shows that all three high-performance materials have significant advantages in improving bridge structural performance, extending bridge service life, and increasing construction efficiency, providing important support for the development of modern bridge reinforcement technology.

The research found that super-strong high toughness resin concrete, with its excellent compressive, crack-resistant, and corrosion-resistant properties, can effectively enhance the structural strength and durability of bridges in extreme environments. Ultra-high-performance concrete, with its outstanding mechanical properties and long-term stability, can significantly enhance the load-bearing capacity and durability of bridges under complex construction conditions. Carbon fiber composite materials, due to their lightweight, high strength, and convenient construction, have shown significant effects in local bridge reinforcement and durability improvement. Additionally, these three materials have demonstrated advantages in shortening construction periods, reducing traffic impacts, and lowering maintenance costs in actual projects, providing efficient and economical solutions for bridge reinforcement projects.

Future research can further explore the application effects of high-performance materials in large-span bridges and special structures, and combine bridge health monitoring technology to analyze their performance in dynamic damage repair. At the same time, the preparation processes and construction procedures of the materials can be further optimized to reduce costs and enhance project adaptability. These studies will not only promote the continuous advancement of bridge reinforcement technology but also contribute to the sustainable development of bridge engineering, ensuring the long-term safety and efficient operation of bridge structures.

References

[1] Zhou Huanqing. Application Analysis of Ultra-High Performance Fiber Concrete in Highway Bridge Reinforcement [J]. Transportation Science and Management, 2024, 5(08): 137-139.

[2] Chen Zhizhong. Research on a New Concrete Bridge Reinforcement Construction Technology [J]. Highway and Transportation Science (Applied Technology Edition), 2020, 16(09): 248-251.

[3] Liu Bin. Application of Super-Strong High Toughness Resin Concrete in Bridge Reinforcement Construction [J]. Transportation World, 2023, (35): 137-139.

[4] Lu Qiong. Application of Super-Strong High Toughness Resin Concrete Technology in Bridge Reinforcement [J]. Transportation Manager World, 2022, (05): 91-93.

[5] Liu Chi, Yu Xiaodong. Research on a New Concrete Bridge Reinforcement Construction Technology [J]. Heilongjiang Science and Technology of Communications, 2020, 43(11): 74-75.

[6] Wang Yi. Application of Super-Strong High Toughness Resin Concrete in Bridge Reinforcement Construction [J]. Jiangxi Building Materials, 2024, (04): 104-105+111.

[7] Zhao Huijun, Li Zhaobin. Super-Strong High Toughness Resin Concrete Bridge Reinforcement Construction Technology [J]. Highway, 2018, 63(11): 145-148.

[8] Zhang Hanling. Research on Bridge Reinforcement Technology Based on Ultra-High Performance Concrete [J]. Engineering Construction and Design, 2024, (17): 216-219. DOI: 10.13616/j.cnki.gcjsysj.2024.09.067.

[9] Amran M, Huang S S, Onaizi A M, et al. Recent trends in ultra-high performance concrete (UHPC): Current status, challenges, and future prospects[J]. Construction and Building Materials, 2022, 352: 129029.

[10] Li J, Wu Z, Shi C, et al. Durability of ultra-high performance concrete–A review[J]. Construction and Building Materials, 2020, 255: 119296.

[11] Qiu Zhimin, Liu Rui, Xiong Zhe. Research Progress on Preparation and Engineering Application of UHPC (Ultra-High Performance Concrete) [J]. Guangdong Architecture Civil Engineering, 2023, 30(2).

[12] Zhang Dongxing. Fiber Reinforced Polymer (FRP) Reinforcement Technology and Its Prospects in Bridge Engineering [C]// Hengshui Jitu Technology Co., Ltd. Low Carbon Concrete Application. Lanzhou Ecological Environment Construction Management Co., Ltd.; 2024: 5. DOI: 10.26914/c.cnkihy.2024.028461.

[13] Sun Hongshui. Research on Design Application of Carbon Fiber Composite Materials in Bridge Reinforcement [J]. Engineering Construction and Design, 2024, (12): 135-137. DOI: 10.13616/j.cnki.gcjsysj.2024.06.243.

[14] Liang Chunxiao. Application Research of Carbon Fiber Adhesive Materials in Bridge Structure Reinforcement [J]. Adhesion, 2024, 51(10): 38-41.

[15] Mu Changjun. Research on the Application of Carbon Fiber Materials in Bridge Reinforcement Engineering [J]. Low Carbon World, 2022, 12(03): 154-156. DOI: 10.16844/j.cnki.cn10-1007/tk.2022.03.060.