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Review

An Overview of the Application of Fiber-Reinforced Cementitious Composites in Spray Repair of Drainage Pipes

Shun Dong [1,*], Dianchang Wang [2], Erqing Hui [2], Chao Gao [1], Han Zhang [1] and Yaosheng Tan [1]

[1] China Three Gorges Corporation, Wuhan 430010, China
[2] Yangtze Ecology and Environment Co., Ltd., Wuhan 430077, China
* Correspondence: dong_shun@ctg.com.cn

Abstract: The structural performance of buried drainage pipes is gradually deteriorating under the influence of external loads and chemical and microbial corrosion. It is crucial to reinforce them and improve their bearing capacity for safe use. One of the important technologies used to extend the service life of deteriorated pipes is the use of fiber-reinforced cementitious composites (FRCC) for spray repair. Combined with the current situation of drainage pipes, this article introduces the basic properties of FRCC, briefly describes the requirements for material performance for drainage pipe spraying rehabilitation, reviews the structural bearing capacity of drainage pipes repaired by spraying with FRCC, and discusses the relevant research and engineering applications of the spraying method. Studies show that FRCC has high strength and corrosion resistance, and excellent sprayability. The structural performance of the host pipe is significantly improved after repair, but measures should be taken to enhance the interfacial bonding performance during the repair. In the design of the liner wall thickness, there is no unified calculation theory, and the existing methods have not considered the influence of secondary load on the structure. It is recommended to combine the type of pipe defects and the degree of deterioration in further study.

Keywords: drainage pipes; cementitious materials; spraying method; structural properties; design theory

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Citation: Dong, S.; Wang, D.; Hui, E.; Gao, C.; Zhang, H.; Tan, Y. An Overview of the Application of Fiber-Reinforced Cementitious Composites in Spray Repair of Drainage Pipes. *Buildings* **2023**, *13*, 1119. https://doi.org/10.3390/buildings13051119

Academic Editors: Bo-Tao Huang, Jing Yu and Hao-Liang Wu

Received: 14 March 2023
Revised: 9 April 2023
Accepted: 19 April 2023
Published: 23 April 2023

1. Introduction

Drainage pipes are an important part of urban underground buildings and city infrastructure. By the end of 2021, the total length of urban drainage pipes in China reached 872,000 km, and the proportion of drainage pipes more than 10 years old was more than 40% (Figure 1). For example, most of the concrete drainage pipes in Beijing, Guangzhou, Shanghai, and other cities are over 30 years old. European and North American countries are faced a large number of aging municipal pipes that are in urgent need of maintenance and renewal. For the problem of aging buried pipes, a variety of trenchless rehabilitation techniques have been proposed, such as cured-in-place pipe, slip lining, spray lining, etc. [1–5]. In recent years, the majority of urban drainage pipes in China have started facing similar problems, with frequent leakage, corrosion, rupture, and even collapse, which adversely affect the safe operation of municipal pipelines and public safety [6–8]. Many cities have started on the renewal of old pipe networks; the investment costs of government departments in pipe network renovation and reinforcement have been rising year by year, and related safety issues around municipal pipe networks are a major consideration for future urban construction in China [9].

Trenchless rehabilitation and renewal technology has gained widespread usage in the rehabilitation of drainage pipes because of its economical and environmentally friendly nature [10,11]. Of these technologies, lining with sprayed cementitious materials is prevalent for the rehabilitation of various drainage pipes and culverts due to its flexible construction, rapid repair speed, superior structural performance, and resistance to corrosion. Lining with sprayed cementitious materials method is a rehabilitation method in which a fiber-reinforced cementitious composite for repair is uniformly coated on the inner surface of the host pipe to form a lined pipe by centrifugal or pressure spraying, as shown in Figure 2. This technology is more widely used in Europe and North American countries; in recent years, China has also started to use this technology for the spraying repair of drainage pipes, and has achieved better repair results [12–15]. At present, the main research related to spraying methods of cementitious materials concerns the development of new fiber-reinforced cementitious composites, and the study of the structural bearing capacity of the repaired structure [14,16–19].

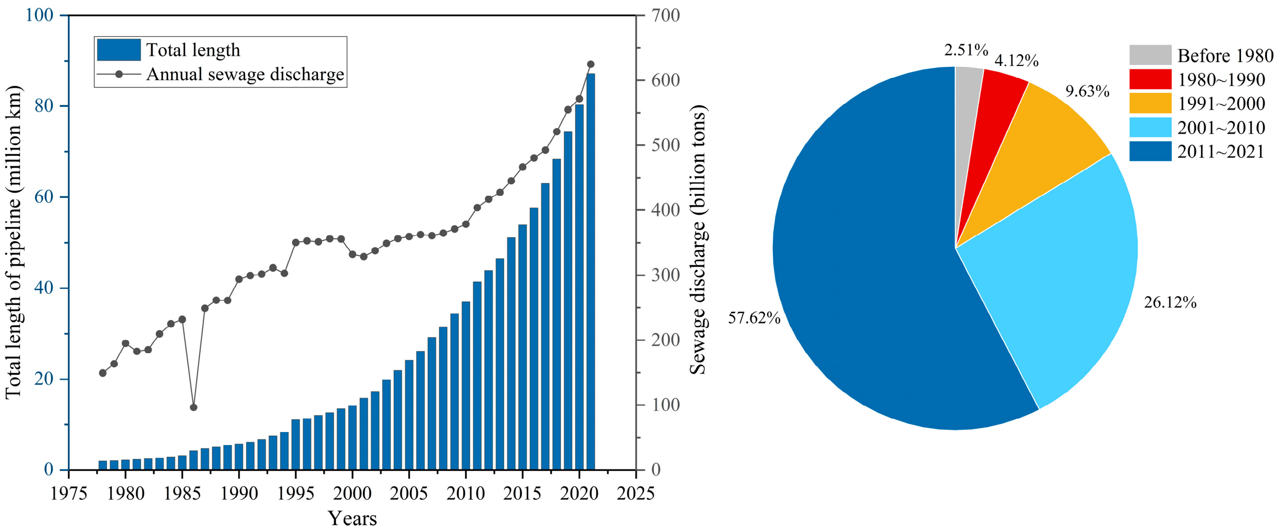

Figure 1. Chart of the growth of urban drainage pipe mileage and the distribution of service life in China.

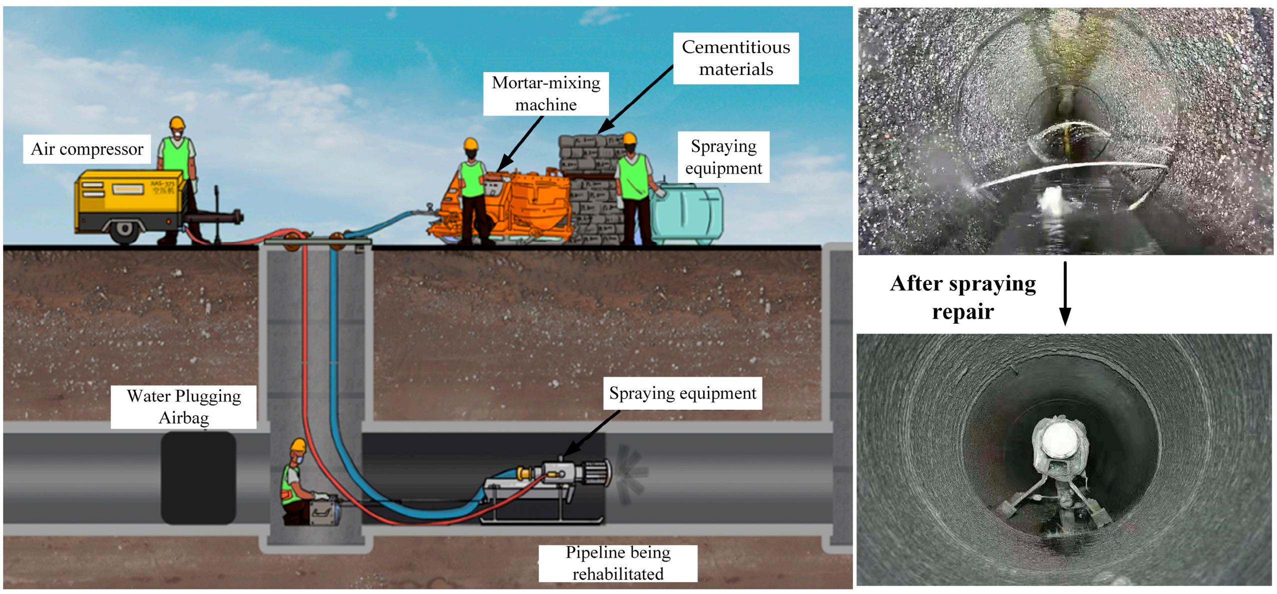

Figure 2. Lining with sprayed cementitious materials for drainage pipe rehabilitation.

Since the introduction of ultra-high-performance concrete, there has been a continuous pursuit of high-performance materials with long service life, high strength, and corrosion resistance. Based on traditional mortar and concrete, millimeter- and micron-sized aggregates are added to improve the compressive and flexural capacity of the material [18–21]. Fiber-reinforced cementitious composites (FRCC) are composite materials with fibers as reinforcing materials and mortar as bonding matrix. The tensile, flexural, cracking, fatigue, vibration, and impact resistance of the material are significantly improved by the addition of fibers. When cementitious materials are used for spraying repair and reinforcement of old pipes, it is required that the repaired pipes can restore or exceed the structural strength of the original pipes, and the lining layer can bear some or all of the external loads alone. The lined pipe mainly fails due to tensile damage and debonding from the interface with the original pipe, so the lining material needs to have good toughness and bonding properties, and deform in concert with the original pipe when subjected to external loads and jointly stressed [14,22]. According to the test results of the bearing performance of the repaired pipe, the corrosion resistance, uniform spraying performance, and interfacial bonding performance of the lining material with the original pipe have a greater impact on the repair effect [14,16,17]. In concrete structure repair and reinforcement, some scholars also proposed the compatibility of repair materials and base concrete, such as volume deformation compatibility, mechanical property compatibility (the compressive, tensile, and flexural strength should be higher than that of base concrete), interfacial bonding compatibility, and permeability compatibility, which provide some guidelines for structural repair and reinforcement design [23–26].

The fiber-reinforced cementitious composite material used in the spraying method is usually a finished dry-mixed mortar material, which can be used only by adding water according to a certain ratio when repairing on site. The main ingredients are high-grade silicate cement, well-graded quartz sand, microsilica powder, reinforcing fiber, a water-reducing agent, a quick-setting agent, etc. In terms of the composition and construction requirements, there is a clear difference from ordinary high-performance or ultra-high-performance concrete: in the absence of coarse aggregates, its performance index can exceed that of some high-performance concrete. For example, high-performance fiber-reinforced cementitious composite materials such as MS-10000 and PL-8000, developed by AP/M, have the characteristics of high strength, durability, and corrosion resistance after adding polypropylene short fibers, with a compressive strength up to 70 MPa and tensile strength around 4.5–5.5 MPa, and so are also widely used in some domestic projects. Some domestic manufacturers have also developed similar special repair mortars, such as the H-70 fiber-reinforced cementitious composite material developed by Wuhan CUG Trenchless Technology Research Institute. The material performance parameters have reached a good level, as shown in Table 1 [14,15,21].

Table 1. Comparison of the performance of different types of mortar materials for spray repair.

Parameter		H-70	MS-10000	PL-8000
Compressive strength (MPa)	24 h	≥25	20.68	20.7
	28 d	≥65	70	55
Flexural strength (MPa)	24 h	≥3.5	2.76	4.1
	28 d	≥9.5	10.34	7.4
Elastic modulus (GPa)		≥30	36	36
Tensile strength (MPa)		-	5.52	4.7
Setting time (min)	Initial setting	≤120	≤120	≤120
	Final setting	≤360	≤240	≤240

With the improvement of the understanding of the structural properties between the lining material and the original pipe, higher requirements for fiber-reinforced cementitious composites have been put forward in terms of mechanical properties, such as the toughness, tensile strength, self-healing properties, and cracking resistance of the material and the bonding performance of the original pipe [14,23,27]. The further development and application of cementitious composites spray construction of trenchless repair technology will be carried out mainly in terms of new lining materials, structural load-bearing performance enhancement, and other related research. In this paper, based on the types of defects and usage environment of drainage pipelines in China, the demand for fiber-reinforced cementitious composites by the spraying method is analyzed, and the research progress and structural performance testing of fiber-reinforced cementitious composites after repair are reviewed. The current research status of lining wall thickness design is discussed, and future research needs are pointed out, providing a reference for the development of new cementitious composite lining materials and the application of cementitious material spraying repair technology for trenchless repair.

2. Survey of Drainage Pipe Defects and Repair Requirements

2.1. Service Environment and Defect Types of Drainage Pipes

Buried drainage pipes are exposed to long-term dampness and sulfate erosion, and are subjected to soil loads around the pipe, groundwater pressure, traffic loads, etc., resulting in various defects to the pipe during operation. Defect detection and defect level determination before pipe rehabilitation are crucial to rehabilitation. The most commonly used pipes for drainage in China are reinforced concrete, high-density polyethylene, and polyvinyl chloride. According to current inspection results, common defects in concrete pipes are corrosion and rupture (including longitudinal and circumferential cracking) (Figure 3), as well as leakage, disconnection, and foreign body penetration, while defects such as rupture and collapse are mostly found in plastic-type flexible pipes [6,7]. In addition to the commonly used circular pipes, some arch-shaped and rectangular drainage culverts built with materials such as bricks, stones, and concrete were constructed in the early days of urban construction. These culverts have been in operation for a long time and exhibit more serious defects such as leakage, corrosion, and collapse [28–30]. Furthermore, drainage culverts are prone to accidents such as soil erosion and ground collapse due to their large cross-sectional dimensions. The percentage of concrete pipe defects in a domestic city is shown in Figure 4.

Figure 3. Common defects of drainage pipes.

The types of defects and causes of damage of drainage pipes have been summarized in some detail in several works; corrosion and rupture are the most common in drainage pipes in China [6,31]. Young et al. summarized the damage types of concrete pipes, mainly longitudinal cracks, circumferential cracks, and joint damage [32]. For the typical damage type of concrete pipes with longitudinal cracks, Ballinger studied the whole process of concrete pipes, from the initial laying to the final damage, through experiments [33]. The corrosion damage inside the concrete pipe is mainly due to the gradual formation of H_2SO_4 when the H_2S gas in the pipe encounters condensed moisture, which rapidly corrodes the inner wall of the concrete pipe, leading to gradual thinning and exposure of the concrete pipe inner wall, reducing the service life of the drainage pipe [34–36].

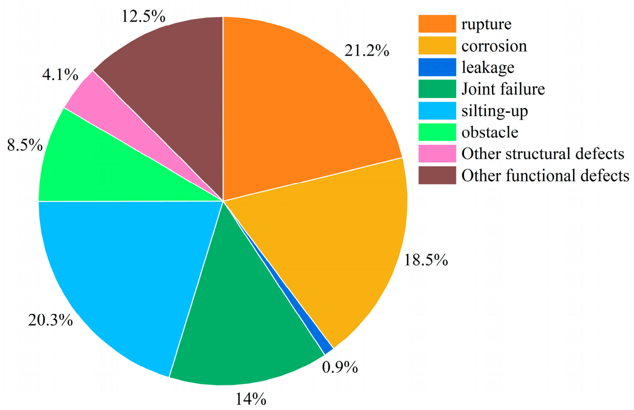

Figure 4. Distribution of concrete pipe defects in a city.

2.2. Requirements for Material Properties of Cementitious Material Spraying Method

According to the common types of defects in drainage pipes, service environments, and structural performance requirements, domestic and foreign scholars have studied various aspects of spray repair materials for drainage pipes [16,17,21,37]. Drainage pipeline spraying repair materials are different from ordinary pipeline anticorrosion lining, mortar, or concrete materials for reinforcement of housing, bridges, etc. The lined pipeline has a complex working environment and needs to bear soil load and groundwater load, jointly or separately with the original pipeline, and requires good durability performance, with a service life of more than 50 years in general. China's drainage pipe trenchless repair standards mainly set requirements for the setting time, compressive and flexural strength, acid resistance, and impermeability of cement mortar materials for spraying (Table 2), and the construction performance requires that the mixed slurry should be suitable for pumping and spraying, can be well bonded on the wet pipe wall surface, etc. [38]. Therefore, the material needs to have good flow properties, and the length of the fiber and the amount of admixture should not be too large.

Table 2. Performance requirements for cementitious materials for structural repair.

Parameter		**Specifications**
Setting time (min)	Initial setting Final setting	≤120 ≤360
Compressive strength (MPa)	24 h 28 d	≥25 ≥65
Flexural strength (MPa)	24 h 28 d	≥3.5 ≥9.5
Elastic modulus (GPa)	28 d	≥30
Adhesion in tension	28 d	≥1.2
Impermeability	28 d	≥1.5 MPa
Shrinkage performance	28 d	≤0.1%
Acid resistance	Corrosion for 24 h (5% sulfuric acid) Corrosion for 48 h (10% citric acid; 10% lactic acid; 10% acetic acid)	No spalling, no cracking

In addition, in order to ensure that the original pipe and the liner work together, the mechanical properties R_{m} and C_{s} of the liner material and the original pipe material need to meet certain criteria to ensure that a good repair effect is achieved, as shown in Figure 5 [39].

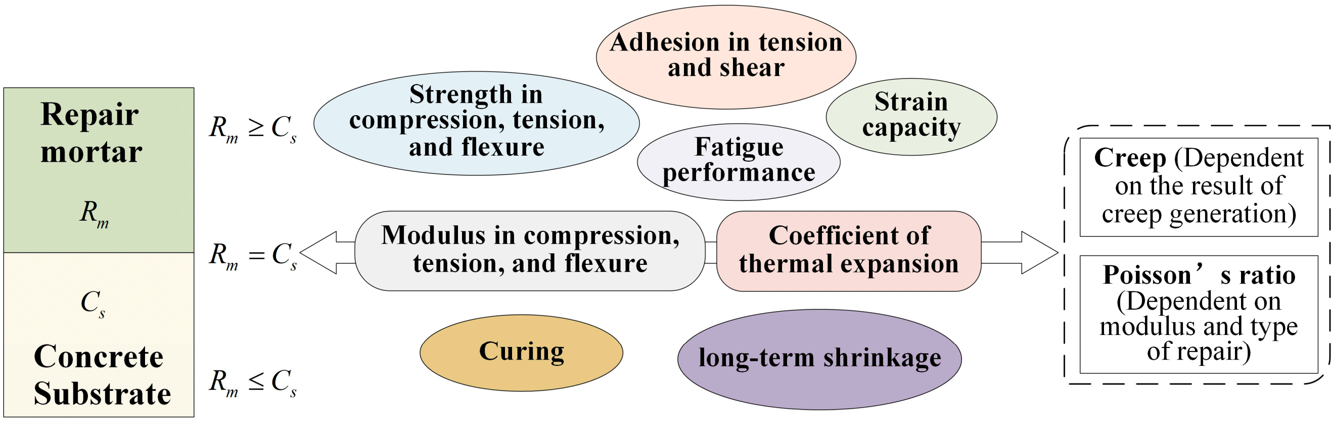

Figure 5. General requirements of structural compatibility for repair mortars.

Combined with the type of load mainly borne by the drainage pipe and the service environment, the main requirements for cementitious material for spray repair are as follows.

(1) Strength of materials

The first requirement for cementitious materials for pipe repair is that the tensile, bending, and compressive strength of the material be higher than that of the original concrete pipe, e.g., compressive strength is generally >50 MPa, much higher than the performance of concrete pipes commonly used in China (compressive strength of ~30 MPa). Another is the elastic modulus of the two, and thermal expansion properties as close as possible. More research on the tensile and flexural properties of the liner is required. Some studies have shown that the mortar lining is mainly subjected to tensile stresses, and the initial damage occurs due to tension. Therefore, the material should have a high tensile strength and good toughness, ensuring that the lined pipe and the host pipe can be deformed in a coordinated manner [27,40].

(2) Durability

Structural spray repair of cementitious materials generally requires a service life of >50 years, and durability is a key consideration for spray repair as sulfate and microbial corrosion are the main causes of structural strength reduction of concrete pipelines. Indoor corrosion tests have shown that the mechanical properties of high-performance cementitious materials are significantly reduced in the corrosive environment of drainage pipes, thereby reducing the effectiveness of spray repair [41]. At the same time, the material's compactness and cracking resistance are factors influencing corrosion resistance. Therefore, cementitious materials for spray repair usually include various fibers to enhance the tensile strength of the material and fine aggregates such as microsilica powder, graded fine sand, and fly ash to increase the denseness of the material in order to increase the durability of the material. According to Wang's research, the combined use of polyvinyl alcohol (PVA) fibers and magnesia expansion agent (MgO) can effectively solve the problems of concrete cracking and abrasion damage. Additionally, fly ash, fibers, MgO, and shrinkage-reducing admixtures can all improve the frost resistance of concrete [42–44].

(3) Interfacial bonding performance

The effectiveness of the rehabilitated structure depends on the weakest part of the combined structure, and for the existing pipe-lined structure, the bonding performance of the interface has a major influence. Zhao et al. showed that the interface peeling between the cementitious materials liner and the original pipe under external load is the main reason for the failure of the combined structure [14,22]. Zhang proposed that the radial stress and shear strength of the interface are the conditions for the liner and the existing pipe to work together, and the presence of the interface gap causes the combined structure to show poorer performance when sharing the external load [27]. McAlpine's study also showed that the liner alone cannot increase the load-bearing performance of the structure, and that the lined pipe needs to be bonded to the existing pipe as a whole, so as to achieve the purpose of improving the load-bearing performance of the repaired structure [40]. In addition, the plastic shrinkage and dry shrinkage strain of cementitious materials can lead to peeling of the interface. The addition of fly ash, microbeads, and mineral powder to cement mortar can all reduce the early shrinkage of cementitious materials, but the high dosing of silica fumes is not conducive to shrinkage control [45]. During the actual repair construction, measures such as high-pressure water cleaning and interface implantation of reinforcement should also be used to increase the bonding properties of the interface in order to improve the load-bearing capacity of the repaired structure.

(4) Sprayability

The lining with sprayed cementitious materials rehabilitation method uses centrifugal or pressure spraying to ensure a good cement-based material evenly covers the host pipe inner surface to form a lined pipe. The cementitious material, under the action of compressed air, is transported through the feeding tube to the nozzle, so it must have good fluidity to ensure pumpability, no sagging, low resilience, and that the length of fibers and dosage are not too high.

(5) Impermeability

Seepage resistance is the main control index to improve and ensure the durability of the structure. Buried pipelines are in an environment of moisture and water erosion for a long time, and the impermeability of lining materials is closely related to the material age, water–cement ratio, additives, etc. In addition, the impermeability is inseparable from the development of crack extension, so the anti-cracking performance, compactness, and self-healing performance of the material are currently focused on in more studies [46–48].

3. Research Progress of Fiber-Reinforced Cementitious Composites

3.1. Introduction to Fiber-Reinforced Cementitious Composites

Since the 1960s, steel fibers, polypropylene fibers (PP), polyethylene fibers (PE), glass fibers and other fiber-reinforced concrete and mortar materials have been developed and applied—mixed into the fiber to limit the formation of cracks, growth, and chemical intrusion; or to solve the problems of poor tensile properties of traditional concrete and mortar materials, material shrinkage, and lack of durability. In the 1980s, the concept of high-performance concrete (HPC), with high strength, durability, and excellent performance was introduced in Europe and the United States. Research ensued related to Ultra-High Performance Concrete (UHPC), based on the mathematical model of maximum packing density theory, by adding millimeter-level aggregates, micron-level fine ash (fly ash, cement, mineral powder), submicron particles (silica fumes), fibers, and various additives—in theory, to achieve the maximum densities; its energy absorption, such as compressive and flexural resistance, is also significantly improved, but the tensile strain of UHPC is 0.2% or even lower [49,50]. The incorporation of fibers in cementitious materials is one of the most effective methods to improve the performance of cementitious materials toward light weight, high strength, high toughness, and high durability at present, gradually forming FRCC materials, which are rapidly developed and applied worldwide. The complex internal environment of buried drainage pipes is susceptible to chemical and microbial corrosion, and the trenchless repair requires the shortest possible construction period and early return to use, which requires the cementitious lining to have good structural strength, corrosion resistance, and fast-setting and early strength properties. To ensure the reliability of the structure for long-term use, it also needs to fit closely and bond well with the original pipe, and fiber-reinforced cementitious materials can meet these needs. When used for drainage pipe repair, these have an obvious effect of crack resistance, enhancement, and toughening, and can also increase the bonding strength between the lining and the original pipe to enhance the repair's effectiveness.

Ultra-high-toughness cementitious composites (UHTCC) or engineered cementitious composites (ECC) are prepared by using cement, fly ash, and other industrial wastes as cementitious materials, forming a matrix with quartz sand, water, and a high-efficiency water-reducing agent, and then mixing with polyethylene (PE) fibers or polyvinyl alcohol (PVA) and other short-cut fibers as reinforcing materials. Compared with FRCC, High-Performance Fiber-Reinforced Composites (HPFRCC), etc., the ultimate tensile strain of ECC exceeds 3%, which is tens to hundreds of times higher than that of ordinary fiber-reinforced cementitious composites. ECC can be designed with different properties by adjusting the parameters of the matrix and fibers. The compressive strength of ECC using high-strength fibers can reach more than 200 MPa, and the elongation performance can exceed 12% [17,51,52]. Moreover, this material has small cracking gaps, good corrosion resistance, and some self-healing ability, which can significantly improve the durability of structures [53–56]. This type of material has been widely used in buildings such as dams and tunnels and has shown good reinforcement effects [37,57–59].

For the design of new materials, Li proposed an integrated platform for material design, structural design, and operation and maintenance, as well as an integrated structural material design approach (ISMD) (Figure 6), which theoretically links the macroscopic performance of the structure to the performance of ECC composites and the selection and optimization of ECC constituent materials [37,60]. This research approach is currently often used in the development of lining materials for spray repair, linking material design with the structural performance requirements of pipelines, in order to develop high-strength, high-toughness cementitious repair materials suitable for pipe repair.

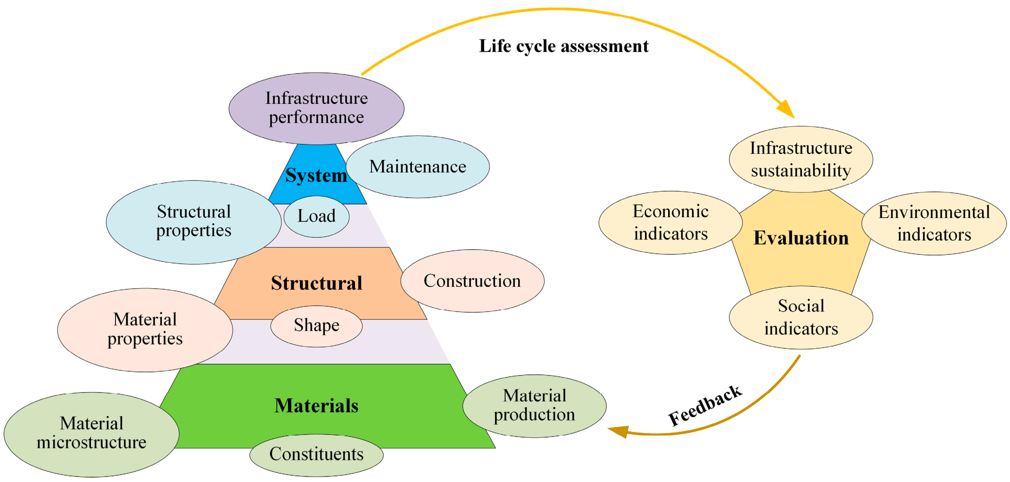

Figure 6. Integrated platform for integrated design of materials and structures.

Matsumoto and Mihashi classified cementitious composites (Figure 7) and introduced the basic concepts and characteristics of various Ductile Fiber-Reinforced Cementitious Composites (DFRCC) [61]. Although the names of these materials are defined differently in each country, the basic design concepts are similar, and new cementitious composites with excellent properties are developed through composition and structural optimization design. Since the properties of ECC materials are very much in line with the needs of drainage pipe repair by spraying, more and more studies have been conducted in recent years on this material in drainage pipe repair, which is also the most promising material for spraying repair [17,62]. The following is an overview of this material in relation to its matrix material, reinforcing fibers, and the fiber–matrix interface structure.

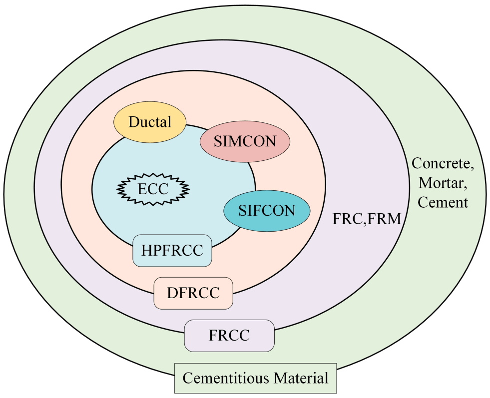

Figure 7. Classification of cementitious composites.

3.2. Matrix Materials

The micromechanical model of an ultra-high-toughness cementitious composite material is a three-phase composite material mechanical model composed of a matrix, fiber, and fiber–matrix interface; the material's microstructure is shown in Figure 8 [37]. Its performance is closely related to the selection of materials such as cement, fly ash, graded quartz sand, water, water-reducing agents, and fibers. In the matrix material, cement is generally selected with higher silicate and aluminate cement grades, and fly ash is added to improve the material's corrosion resistance and self-healing properties. The addition of fly ash can significantly improve the densification and strength of the material, while reducing the dry shrinkage rate of mortar and improving the material's resistance to sulfate corrosion [63]. The study of Yang et al. shows that, although the addition of fly ash can greatly improve the shrinkage resistance of ECC materials, excessive amounts can reduce the compressive strength of ECC [64]. The water–cement ratio of ECC materials is generally around 0.25–0.3, which can be used as the basic proportion of ideal spray repair ECC materials [62,65]. In Kim et al.'s research, the sprayed ECC, as shown in Table 3, used aluminate cement to replace 5% of silicate cement, adjusted the rheological properties of ECC, shortened the material's static stop time, and ensured its pumpability and spray bonding performance [66]. It has been proven that the material performance of the ECC material for spray construction is basically the same as that of the ECC material for mold construction, which shows that the ECC material has good sprayability [67]. Some commonly used matrix materials are shown in Figure 9. In order to ensure the effect of drainage pipe repair, various chemical additives are also added to the material to improve the performance of the repaired structure [68,69].

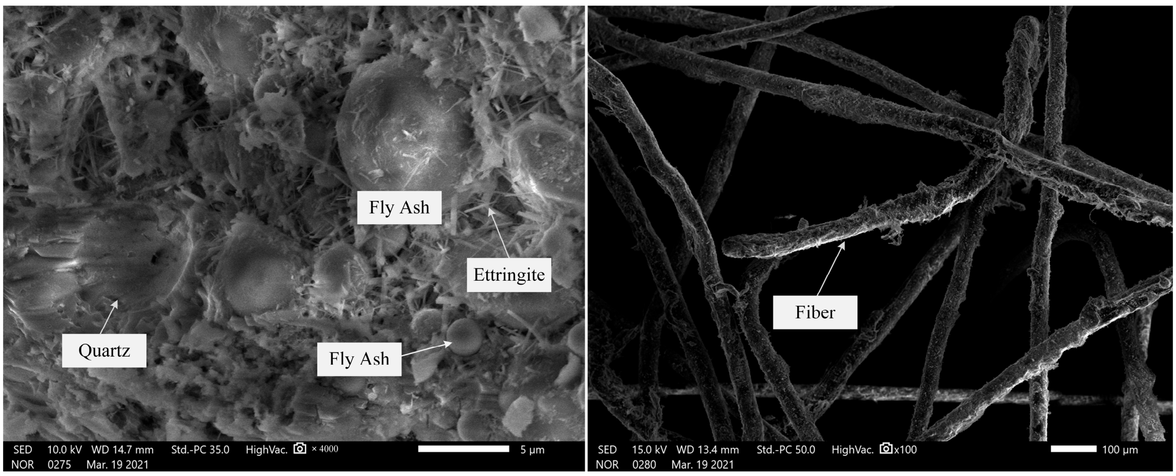

Figure 8. Microstructure of ultra-high-toughness cementitious composites.

Table 3. Typical mix ratio of ECC materials sprayed.

Cement	Water	Sand	Fly Ash	Hydroxypropyl Methyl Cellulose	High-Efficiency Water-Reducing Agent	Aluminate Cement	Fiber (Volume Fraction)/%
0.95	0.46	0.80	0.30	0.0005	0.0075	0.05	0.02 [1]

[1] Except for fiber, the content of each raw material is the mass fraction.

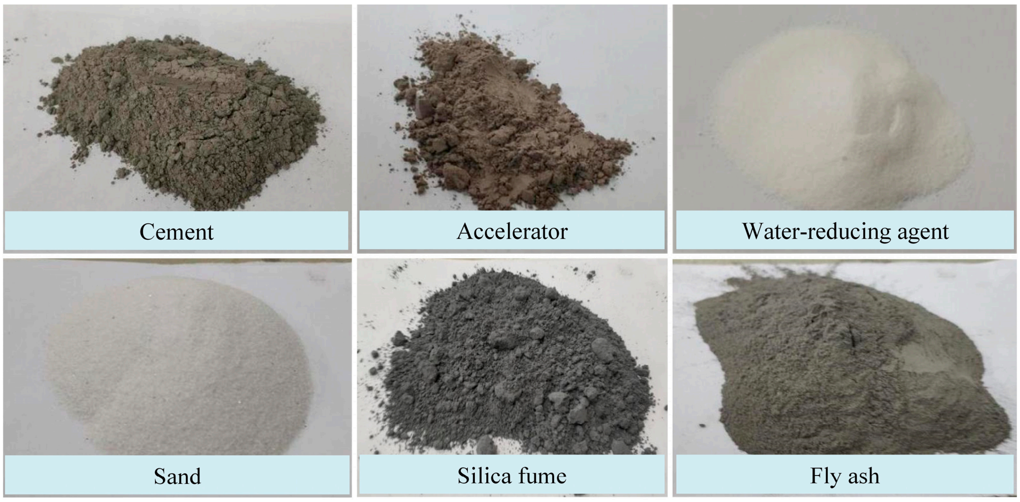

Figure 9. Some commonly used matrix materials.

3.3. Fibers for Reinforcement

The selection of fibers for fiber-reinforced cementitious composites mainly considers the tensile strength, modulus of elasticity, elongation, and bonding with the matrix material of the fibers. The commonly used fiber types and parameters are shown in Table 4 [65,66].

Table 4. Commonly used fibers for fiber-reinforced cementitious composites.

Types of Fibers	Length (mm)	Diameter (μm)	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%)
Polypropylene fiber (PP)	8~20	12	0.91~0.97	850	6.0	21
Polyvinyl alcohol fiber (PVA)	8~12	39	1.3	1600	42.8	6~8
Polyethylene fiber (PE)	8~18	20~38	0.97	3000	100	2~3
Steel Fiber	6~15	100~1000	7.8	350~3000	210	2~4
Alkali-resistant glass fiber	5~20	13~15	2.4~2.76	2000~4000	70~80	2~3.5
Basalt fiber	15~30	6~20	2.6~2.8	2230~4840	85.8~89	2.8~3.1
Carbon Fiber	3~6	5~10	1.57~1.8	525~4660	33~268	0.8~2.4

Mortar with added fibers has excellent anticracking and strength enhancement effects, which can effectively prevent the emergence and expansion of structural cracks and develop the failure type from brittle damage to ductile failure. At the initial stage of bearing load, fiber and cement matrix work together; when the external load increases and cracks start to appear, stress is transferred from the matrix to the fiber through the interface, and the bridging role of the fiber starts to come to the fore, which obviously improves the toughness. The role of fibers is mainly to:

(1) Improve the tensile and flexural strength, etc.
(2) Improve the anticracking ability, effectively reduce cracks caused by the plastic shrinkage and dry shrinkage of the material, prevent the appearance of microcracks in the material, and delay the development of new cracks.
(3) Improve the toughness and impact resistance of the material, bear the tensile stress at the location of the crack so that the material has good toughness.
(4) Improve the seepage resistance, durability, etc. of the material.

The volume fraction, orientation, shape, size, and properties of fibers, as well as the bonding characteristics between the matrix and fibers, are important factors that affect fiber-reinforced cementitious composites. They need to be considered in the design of lining materials [70,71]. PP, PE, and PVA fibers are the most commonly used reinforcing fibers for ECC materials. The elastic modulus of the PP fiber is lower, and its elongation at the break is greater than that of concrete. Its addition can improve the ductility of the material and has an important role in the bearing capacity after cracking. The elastic modulus and tensile strength of PE fiber are higher than those of PP and PVA fibers. The tensile performance of PE-ECC materials is much higher than that of composite materials with PP and PVA fibers. The performance parameters of cementitious composites reinforced with PP, PE, and PVA fibers are shown in Table 5 [72]. Fibers with a high elastic modulus are mainly used to improve the material's impact resistance, tensile and flexural strength, stiffness, and anti-cracking performance, while fibers with a slightly lower elastic modulus are mainly used to improve the material's toughness and strain capacity. Lai et al. studied the influence of PP fiber length and dosage on the flow performance of the material. The results showed that fiber length had a significant effect on the flowability of mortar within the range of 6–12 mm. The fiber dosage was negatively correlated with flowability, and the mass ratio of fiber dosage generally should not exceed 0.9%. The study also showed that mortar materials containing PP fibers can achieve good flowability with reasonable design proportions, which is beneficial for spray construction [73]. On the other hand, Pereira et al. studied the effect of fiber diameter on the initial cracking strength. Fibers with smaller diameters significantly improved the initial cracking strength of the material, while fibers with larger diameters often played a significant role only after cracks formed, showing more obvious tensile hardening characteristics [74]. The carbonation resistance of concrete is also an important factor affecting the durability of structures. Relevant tests have shown that when the length of PVA fiber is 6 mm and the fiber volume content is 0.75%, the improvement of the carbonation resistance of concrete is the strongest [75].

Table 5. Performance parameters of some typical fiber-reinforced cementitious composites.

Type of Fiber	Fiber Content (%)	Initial Cracking Tensile Strength (MPa)	Ultimate Tensile Strength (MPa)	Ultimate Strain (%)	Crack Width (μm)
PVA	0.75~2.5	2.6~4.0	3.9~5.0	1.4~4.6	42~71
PP		1.4~3.2	2.3~4.3	0.8~3.9	63~258
PE		4.4~8.3	6.6~11.9	3.4~9.6	50~150

3.4. Fiber–Matrix Interface

Ultra-high-toughness cementitious composite materials exhibit significant strain-hardening characteristics, excellent strength, and toughness through the rational design of matrix materials, fiber parameters, and interface properties. The effectiveness of fiber-reinforced cementitious composites' mechanical properties largely depends on the interaction between the fiber and matrix, mainly the physical and chemical bonding strength, frictional bonding strength, and mechanical anchoring effect caused by fiber shape change [76,77]. For example, PVA fibers are widely used in ECC materials because they are hydrophilic materials, and their surfaces can form strong chemical bonds with cement matrix, while PE and PP fibers have very weak adhesion to the matrix, and relative slippage easily occurs. To improve the toughness of fiber-reinforced composites, the fiber shape can be changed or the fiber surface can be treated. For example, surface coating can be used to change the fiber's hydrophilic properties and obtain ideal interface properties [77,78]. Plasma treatment of polyethylene fibers can significantly improve the fiber–matrix interface bonding strength, as well as the tensile strength and strain energy of the specimens [79,80].

The stress transfer mechanism between the fiber and matrix material is different before and after cracking when the fiber-reinforced cementitious composites members bear the load. Before cracking, the fiber and matrix material have very little deformation and are in the elastic deformation stage, and they can generally achieve coordinated deformation and shared stress. Because of the different mechanical properties of the fiber and matrix material, the size of the load borne is also different. At this stage, the shear stress appears at the fiber–matrix interface, which is the main factor to consider with regard to crack development. As the deformation increases with the load, the fiber and matrix interface exhibit slip and debonding, and the fiber provides a bridging effect for the component to suppress crack expansion and occurrence. The ultimate strength of fiber-reinforced cementitious composite components appears in this stress transfer mode. The fiber–matrix interface bonding parameters are usually determined by single-fiber pull-out tests, and the fiber–matrix debonding model is determined based on experiments and fracture mechanics methods, providing a basis for the study of cracking mechanisms and material design [81,82].

4. Performance of Repaired Structures

4.1. Structural Performance Testing of Combined Beams

The load-bearing capacity and durability of the rehabilitated structure are the main evaluation indexes of the rehabilitation effect. For the structural performance after repair, domestic and foreign scholars mainly carried out composite beam loading, a three-edge bearing test, and a buried pipe test, and conducted research on the load-bearing performance and interfacial bonding performance of the combined beam and repaired pipe [14,83,84].

The performance of concrete structural repair and reinforcement depends on the bonding quality between the repair material and the substrate material. The interfacial bonding force between new and old structures is composed of mechanical interlocking force, van der Waals force, and chemical action. Currently, measures such as adding cement slurry, an interface treatment agent, and anchoring reinforcement are often used to improve interfacial bonding performance on the existing structure surface. Lim et al. studied the bonding behavior between ECC and the concrete substrate interface using concrete beams with T-shaped notches, which showed that ECC repair and reinforcement can prevent the delamination and peeling of composite structures, and proposed a crack propagation mechanism of ECC and the concrete interface [85]. Wang et al. studied the bending performance of reinforced concrete beams with UHTCC reinforcement through four-point bending tests, and the cracks during the loading process of the composite structure were relatively fine, showing obvious ductile failure. After reinforcement, the structural ductility and load-carrying capacity were significantly improved [86]. Kim et al. conducted bending tests on reinforced concrete beams with sprayed ECC and compared them with other mortar materials. After ECC spray repair, the interfacial performance and energy absorption capacity were better, and the enhancement effect on the load-carrying capacity and ductility of the composite structure was good, which can effectively extend the service life of the repaired structure [48]. Zhang and Zhao et al. studied the judgment criteria for the collaborative work of the original pipeline–inner lining structure after repair through indoor composite beam bending loading tests and theoretical calculations, namely the relationship between the shear strength and bonding tensile strength of the interface and the interfacial shear stress and radial tensile stress. When the resistance is greater than the load, a laminated structure is formed; otherwise, a composite structure is formed [14,27].

Kamada et al. conducted bending tests on reinforced concrete beams with ECC and investigated the effect of concrete surface roughness on the fracture behavior of composite structures. The results showed that smoother concrete surfaces were more favorable for the long-term use of repaired structures [87]. Xie et al. divided the interface between new and old concrete into a permeation layer, a strong influence layer, and a weak influence layer, and discussed the relationship between the microscopic structure of the interface and the macroscopic mechanical properties [88]. Qian et al. proposed a test method using a conical hole specimen to evaluate the bonding properties of cementitious repair materials and compared it with the existing bending method. The bonding performance was evaluated by examining the bonding appearance and testing the permeability of the interface and the bonding strength [89]. Xu et al. studied the interface bonding behavior between sprayed ultra-high-toughness cementitious composite materials and concrete structures, and showed that the spraying direction and surface roughness had a significant effect on the interface bonding performance. It was also pointed out that the thickness of a single continuous spraying should not exceed 25 mm during spraying construction, and layer-by-layer spraying should be used for thicknesses greater than 25 mm [90]. Huang found that, as the thickness of the UHTCC layer increased, the stiffness, yield load of steel bars, and ultimate load of beam specimens also increased, and the occurrence of cracks in the concrete layer could be effectively controlled after spraying. In addition, layer-by-layer spraying construction of the reinforced layer did not affect the reinforcement effect compared to the single-layer spraying process [59].

Split tensile strength testing, direct tensile strength testing, and shear testing of cubic specimens are also commonly used to evaluate the bond strength of interfaces. Cheng et al. systematically studied the bonding between fiber-reinforced concrete and substrate concrete through experimental research, exploring the basic mechanical properties of shear and split tensile strength as well as the antifreeze and antiseepage capacity and durability of the bonding surfaces [91]. Wang et al. studied the tensile bond strength between UHTCC and concrete substrate through pull-out tests, investigating the influence of the interface roughness, substrate strength, interface bonding agent, and other factors on the tensile bond strength, and showing that improving substrate strength, reasonable substrate surface roughness, and interface bonding agent are favorable for forming a good bond at the interface [92]. Interfacial implantation of reinforcement has also been used to increase the interfacial bond strength. Yang et al. studied the mechanical properties of the reinforced UHPC–masonry interface, showing that the failure mode of unreinforced UHPC–stone combination specimens is brittle, while the reinforced specimens exhibit ductile failure mainly characterized by interface slip and local stone splitting, and the interface shear strength is significantly increased after reinforcement [93].

From a previous study, we know that the bonding performance of the interface has a significant impact on the strengthening effect of structures. However, currently, few measures are taken to enhance the bonding strength of the interface before repair construction, and most of them only use high-pressure water washing, which has limited synergistic performance between the original pipeline and the lining. More measures should be taken to increase the bonding performance of the interface between the lining and the pipeline, such as increasing the roughness of the inner wall of the pipeline through mechanical action, implanting a reinforcement at the interface, adding a wire mesh, and increasing the use of interface treatment agents to improve the shear, tensile, bending, etc. performance of the interface. For repairing drainage pipelines that require a thicker lining, a layered spraying method should be adopted.

4.2. Three-Edge Bearing Test

For the rehabilitation of drainage pipes by cementitious materials spraying, excellent load-bearing performance after rehabilitation is the goal of material development and is a great concern for management, designers, and construction personnel. Cementitious materials development should consider the need for material performance in conjunction with the force model of the pipe–lining structure. A three-edge bearing test is often used to evaluate the load-bearing performance and defect level of drainage pipes before and after rehabilitation, which provides a reference for lining design and structural performance evaluation.

Najafi et al. studied the changes in the load-bearing capacity of a 610-mm-diameter reinforced concrete pipeline after repair, and found that the use of cementitious lining with thicknesses of 12.7 mm and 25.4 mm increased the load-bearing capacity by 25% and 77%, respectively [94]. Kang et al. found that a cementitious lining greatly reduced the stress on the steel corrugated pipe and, under external loads, the top of the lining was most likely to produce tensile cracks. Therefore, the design control parameter was the tensile strength of the lining, rather than deformation [95]. Zhao et al. repaired a 1000-mm-diameter reinforced concrete pipeline with four longitudinal cracks using spray repair, and tested the performance changes of the repaired structure through three-edge bearing tests. They pointed out that there were differences in the repair effects given different deformation amounts of the original pipeline. When the deformation amount was less than 2.7%, the repair effect was better, and the structural strength with a 50 mm lining was greater than the ultimate bearing capacity of the original pipeline. When the deformation amount was greater than 2.7%, the repaired structural strength was still lower than that of the original pipeline [14]. Zhu and Wang et al. used ECC to repair concrete pipelines, and the test results showed that the load-bearing capacity of the repaired structure was about four times that of the original pipeline, and the antipermeability performance was better [17,62]. Fan et al. carried out spray repair and reinforcement on reinforced concrete pipelines with different degrees of damage (70%, 80%, and 90% of the ultimate load), and found that the ultimate bearing capacity of the repaired pipeline increased by 50.6%, and the lining did not separate from the original pipeline [96]. Wang et al. used H-70 cement mortar to spray reinforce damaged shield tunnel segments, and full-scale loading test results showed that the ultimate bearing capacity of the structure increased by 10% after reinforcement [15]. The test results of Entezarmahdi et al. showed that the flexural and compressive properties of concrete pipes were significantly improved after repairing with cementitious materials [97].

According to a previous study, the rehabilitation of drainage pipes with different degrees of defects can achieve different rehabilitation results. The probability of failure of buried pipes during service can be described according to the bathtub curve (Figure 10), which shows that the probability of failure of the original pipe increases gradually with an increase in service time; the probability of failure increases significantly beyond the normal service stage and the remaining bearing capacity becomes smaller and smaller. Choosing a reasonable time to repair, at or before the failure stage, is conducive to extending the service life of the pipeline. On the contrary, when the original pipeline has more serious damage, the repair requires a higher wall thickness and cannot make full use of the remaining bearing capacity of the existing pipeline and the ability of the two to work together, and the service life is not significantly improved.

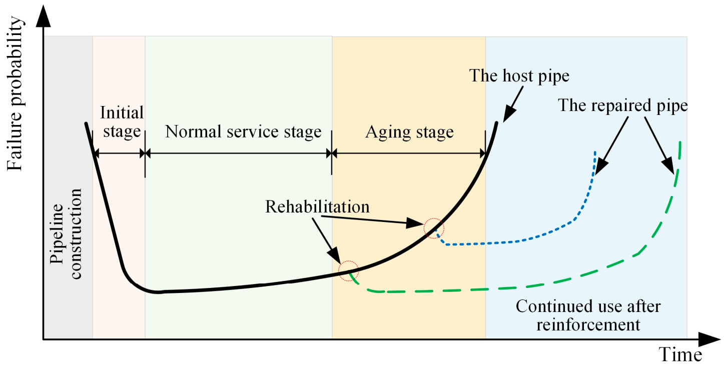

Figure 10. Effect of different repair times on service performance after repair.

4.3. Soil–Pipe–Liner Structural Performance

Pipe soil model tests can simulate the actual stresses on buried pipes and provide a reference for repair design. Law and Moore proposed the concept of a soil–host pipe–lining pipe interaction when they studied the structural performance of HDPE-lined repair of damaged plain concrete pipes [98]. It was shown that the stiffness contributed by the soil on the pipe side was approximately twice the stiffness contributed by the liner and the liner plus a grouting layer [99]. Moore et al. conducted cementitious material spray repair tests on internally corroded steel-walled corrugated pipes and showed that the flexural stiffness of the pipe section increased after the spray repair and the bending moment of the original pipe section decreased. The study pointed out that the original pipe and the cement mortar lined pipe are not fully bonded and so cannot work together, and the tensile strength of the liner is only 7% and 13% of the ultimate tensile strength of the material when the liner is 76 mm and 51 mm. The bonding effect between the two should be ignored for conservative calculations during the repair design. It has been proposed that the damage mode of cement mortar lining is brittle rupture due to circumferential bending, and that lined pipes are not susceptible to buckling [83,100,101]. Zhang et al. studied the effects of traffic load, earth pressure, and groundwater load on the structural performance of concrete pipes repaired by cement mortar spraying, showing that traffic load and earth pressure have a large effect on the structural bearing performance. The spraying repair can reduce the stress concentration in the corroded area of the pipe and restore the load-bearing performance of the original pipe to even greater than that of the original pipe [102,103]. Tetreault et al. conducted spray repair of corrugated steel pipes buried at a depth of 0.45 m with artificial corrosion and tested the structural performance of the pipe under traffic load before and after the repair. The study showed that the ultimate load carrying capacity of the rehabilitated pipe increased from 1325 kN to 1600 kN [104]. Other studies have shown that the damage deformation of the original pipeline is relatively small, and the lining pipeline bears very little earth pressure [105]. However, for buried pipelines, the study of soil–pipe interactions is necessary for accurate rehabilitation design and prolonging the service life of the structure.

5. Wall Thickness Design of Liner

Although a large number of structural performance tests and theoretical studies have been conducted previously, there is no fully unified method for liner wall thickness design. Bazant et al. considered the size effects of fracture mechanics and proposed a method for calculating the thickness of concrete beams and rings [106]. According to the different damage types of the original pipe classified in ASTM F1216, Matthews proposed a method for calculating the wall thickness of geopolymer cement mortar lining for partially damaged and completely damaged pipes [107]. Royer et al. considered the effects of safety factor and original pipe ellipticity and proposed a theory of liner wall thickness calculation under different force models based on the study of Young and Watkins [108–110]. The ASTM F1216 calculation method for CIPP liner wall thickness design was also used in the wall thickness design of cementitious lining [111]. The abovementioned liner wall thickness calculation theories have been applied in different situations. Some of the cementitious liner wall thickness calculation methods are shown in Table 6.

Table 6. Cementitious lining wall thickness calculation equation.

References	Calculation Equation	Parameter
[106]	$t = \lambda_0 d_a \left(\frac{\pi t^2 B f_t'}{6 q_t r} \frac{C}{N} \right)^2 - \lambda_0 d_a$	t is the wall thickness of the liner. λ_0, B are empirical constants that characterize the structure geometry. d_a is the maximum aggregate size. f_t' is the direct tensile strength of the liner. N is the safety factor. C is the ovality reduction factor.
[107]	a. partially deteriorated pipe : $t = \sqrt[2.5]{N \frac{P_w l r^{1.5} (1-\mu^2)^{0.75}}{0.807 E_L}}$ b. fully deteriorated pipe : $t = \sqrt[2.5]{N \frac{q_t l r^{1.5} (1-\mu^2)^{0.75}}{0.807 E_L}}$	P_w is the external hydrostatic pressure due to groundwater. l is the effective length caused by surface traffic wheels. r is the inside radius of the host pipe. μ is the Poisson's ratio of the liner. E_L is the long-term elastic modulus of the liner.
[108,109]	$t = \sqrt{\frac{0.0744 q_t \cdot r^2}{\sigma_F} \frac{N}{C}}$	σ_F is the normal stress of a beam in plane bending.
[108,109]	$t = \sqrt{\frac{7.0464 \cdot q_t \cdot r^2}{w \cdot E_L} \frac{N}{C}}$	w is the crack width.
[108,110]	$t = \sqrt[2.5]{\frac{q_t \cdot l \cdot r^{1.5} (1-\mu^2)^{0.75}}{0.807 E_L} \frac{N}{C}}$	The symbols' meaning is as above.
[111]	a. partially deteriorated pipe : $t = \frac{D_0}{\left[\frac{2 K E_L C}{P_w N (1-\mu^2)} \right]^{\frac{1}{3}} + 1}$ b. fully deteriorated pipe : $t = 0.721 D_0 \left[\frac{N^2 {q_t}^2}{C^2 E_L R_w B' E_s'} \right]^{\frac{1}{3}}$	D_0 is the inner diameter of the host pipe. K is the enhancement factor of the soil and existing pipe adjacent to the new pipe. R_w is the water buoyancy factor. B' is the coefficient of elastic support. E_s' is the modulus of the soil reaction.

However, these design methods do not explicitly consider the effect of secondary stress on the pipeline structure. Before repair, the drainage pipeline has already been subjected to loads such as soil pressure, traffic load, and groundwater pressure, and the pipe wall structure has already reached a high stress level and undergone deformation. The internal forces of the pipe wall can be calculated using traditional structural mechanics methods. After repair, the weight of the inner lining layer is borne by the original structure. Assuming that the original structure's load-bearing capacity does not change, the inner lining pipeline can be considered to only bear the part of the load that increases after partial repair, such as newly added ground loads and traffic loads, and does not participate in sharing the loads that already existed before the repair. Therefore, the repair process of drainage pipelines belongs to the category of secondary stress structures, which can cause significant differences in the stress models of existing pipeline–inner lining structures. Although Shi et al., based on experimental results using the helical winding method, showed that the difference between secondary stress and primary stress is small, the crack load and failure load under secondary stress conditions are about 97.3% and 87% of the primary stress model, respectively, and therefore the effect of secondary stress can be considered negligible [112]. However, for pipelines with different types of defects, the extent of the effect of secondary stress has not yet been determined and further research is needed.

6. Lining with Sprayed Cementitious Materials

The main advantage of lining with sprayed cementitious materials is that the construction is flexible, the repair effect is reliable, the lining fits closely with the original pipe, and the overflow capacity and structural bearing performance of the original pipe can be significantly improved. For round pipes, centrifugal spraying equipment can be used for automatic spraying repair, and for rectangular, arched, and other shapes of culverts, manual spraying can be used for construction. In addition, it is possible to assign the spraying thickness flexibly according to the defect level, and decide whether to add reinforcement mesh as needed to meet the structural repair needs.

Lining with sprayed cementitious materials is widely used in China's drainage pipes, box culverts, inspection wells, and other infrastructure, and is applicable to the structural repair of various drainage pipes with diameters from 300 to 3000 mm. When the pipe diameter is less than 600 mm, it can be repaired by automatic centrifugal spraying, with a single spraying thickness of 30 mm and a spraying length of 120 m or more. For a project DN300 reinforced concrete drainage pipe that has been operating for 25 years, there is serious corrosion, leakage, and other defects; the pipe situation before and after the use of centrifugal spraying repair is shown in Figure 11. For a large-diameter drainage pipe, manual spraying repair can be used with distances up to 600 m. The technology to repair a formation of uniform and dense lined pipes, the original pipe to form a good bond, and flexible construction, can be used for bending, misalignment, and other special location repair, with the lining thickness determined according to the actual defects in the specific parts of the adjustment, according to the structural defects that are to be reinforced.

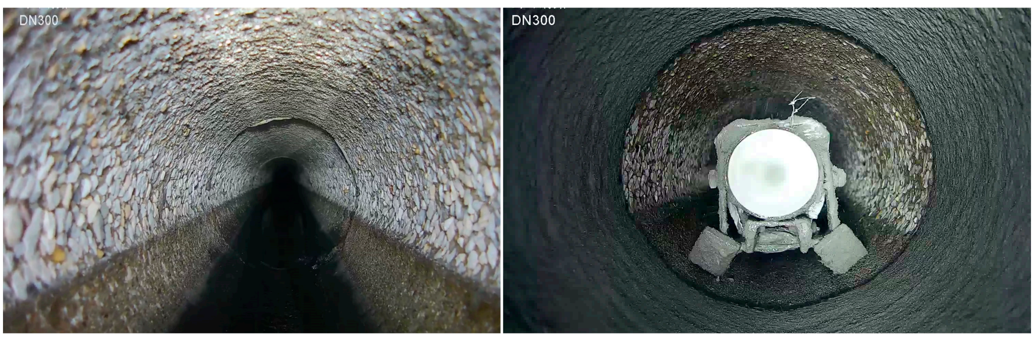

Figure 11. DN300 small-diameter drainage pipe centrifugal spray repair.

The spraying method has been used frequently for the rehabilitation of drainage pipes of other types in China; e.g., when the original pipe is FRP sandwich class with a smooth surface or poor structural performance, the overall performance of the original pipe and the lined pipe can be increased by adding a steel wire mesh to improve the structural bearing capacity after repair. For example, in Chongqing, for a 2000 mm diameter FRP pipe with internal rupture, collapse, and other structural defects, to the original pipe was added a layer of 8 mm diameter spacing of 100 mm reinforcement mesh, and after MS-10000 material manual spraying repair to good operating condition, the wall thickness of the liner was 80 mm, as shown in Figure 12. In addition, the cement-based material spraying method is often used for the rehabilitation of drainage pipe manholes in China (Figure 13).

Figure 12. Manual spraying of fiber-reinforced cementitious composites to repair DN2000 FRP pipes.

Figure 13. Fiber-reinforced cementitious composites for manhole rehabilitation.

At present, most drainage pipe rehabilitation only uses CCTV inspection to artificially determine the type and grade of defects, and then calculates the wall thickness according to the standard, without detailed consideration of the service environment and remaining strength of the pipe, so the design and rehabilitation construction are unreasonable. After detailed inspection, the remaining bearing capacity of the original pipe should also be judged, the service environment of the lining material should be determined, and specific rehabilitation targets should be identified to design the wall thickness, reinforce the mesh parameters of the lining, etc. When selecting cementitious materials, the type of defects, bearing capacity, and construction technology of the original pipeline should also be taken into consideration. A refined rehabilitation design is more conducive to improving structural safety performance and reducing construction costs. The main construction process of this technology should be carried out according to Figure 14. When using fiber-reinforced cementitious composite material spraying to repair drainage pipes, the inner wall of the original pipe needs to be thoroughly clean and without any loose debris, and there should be no water seepage in the pipe. The thickness of one spraying should be less than 30 mm, and the lining wall thickness should be sprayed in layers when it is too large. Attention should also be paid to the influence of temperature and humidity; otherwise, these can have a great impact on the performance of the material.

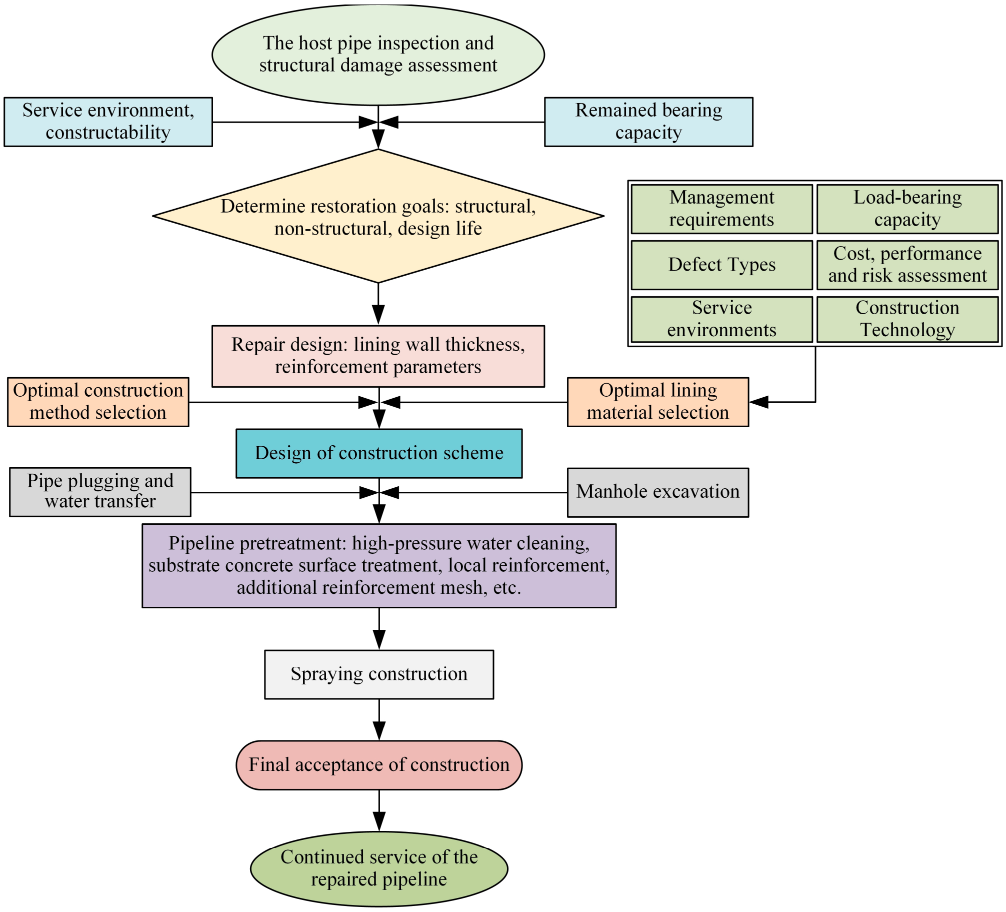

Figure 14. The process of lining with sprayed cementitious materials.

7. Conclusions

The method of lining with sprayed cementitious materials can be used for various types of drainage pipe rehabilitation and is currently used in infrastructure such as subway tunnels and utility tunnels. Through a comprehensive study of cementitious materials' post-rehabilitation structural performance, rehabilitation design, and construction, the following main conclusions were reached.

(1) When the method of lining with sprayed cementitious materials is used for drainage pipe repair, the repair effect is closely related to the performance of the lining material. The lining material for rehabilitation should have excellent structural strength, durability, impermeability, sprayability, etc., and can be firmly bonded and synergistically stressed with the original pipe.

(2) Research on fiber-reinforced cementitious composites for spray repair should be conducted in terms of three aspects: matrix material, reinforcing fiber, and the role of the fiber–matrix interface. It is also necessary to design the material properties in conjunction with the structural stresses of the lined pipe and according to the actual needs of the structure.

(3) Ultra-high-toughness cementitious composites with excellent toughness, structural strength, and durability in the drainage pipe spray repair have gradually begun to be applies. The use of ultra-high-toughness cementitious composites is conducive to

the repair of the structure to bear the load and improve the overall service life of the structure.

(4) Although there have been a large number of structural performance tests and theoretical pieces of research, there is no fully unified lining wall thickness design method. A buried pipeline–nonexcavation repair lining system is a secondary force structure; there has been no research in this area and so further theoretical and experimental work is needed.

(5) Fiber-reinforced cementitious composite spraying technology can be used for the repair of drainage pipes of various section shapes and sizes, with flexible construction and reliable repair results, and can lay reinforcement mesh and design wall thicknesses as required, which has obvious advantages when used for the nonexcavation repair of urban drainage pipes.

In the future, as a large number of drainage pipes in China reach the end of their service life, the demand for fiber-reinforced cementitious composite lining materials will gradually increase. Considering the change of service environment and the demand of structural performance, it is necessary to further develop high-performance fiber-reinforced cementitious composites, such as underwater dispersion-resistant mortar, and construction with water spraying. In terms of indoor tests, there have been few studies considering the overall soil–pipe–liner structure and secondary stresses on the structure, and even fewer studies on in situ testing in the field. It is recommended that further relevant tests and theoretical studies be conducted to provide better information for the assessment of structural performance and liner wall thickness design after repair.

Author Contributions: Conceptualization, S.D.; formal analysis, C.G. and H.Z.; investigation, S.D.; resources, E.H.; writing—original draft preparation, S.D.; writing—review and editing, S.D. and Y.T.; supervision, E.H.; project administration, D.W.; funding acquisition, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the project "Research on cementitious material for drainage pipe rehabilitation and liner thickness estimation" of the China Three Gorges Corporation (Program No. WWKY-2021-0275).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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