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Review

Feasibility of Repairing Concrete with Ultra-High Molecular Weight Polyethylene Fiber Cloth: A Comprehensive Literature Review

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Abstract: This review explores the use of Ultra-High Molecular Weight Polyethylene (UHMWPE) fiber cloth as an innovative solution for the repair and reinforcement of concrete structures. UHMWPE is a polymer formed from a very large number of repeated ethylene (C_2H_4) units with higher molecular weight and long-chain crystallization than normal high-density polyethylene. With its superior tensile strength, elongation, and energy absorption capabilities, UHMWPE emerges as a promising alternative to traditional reinforcement materials like glass and carbon fibers. The paper reviews existing literature on fiber-reinforced polymer (FRP) applications in concrete repair in general, highlighting the unique benefits and potential of UHMWPE fiber cloth compared to other commonly used methods of strengthening concrete structures, such as enlarging concrete sections, near-surface embedded reinforcement, and externally bonded steel plate or other FRPs. Despite the scarcity of experimental data on UHMWPE for concrete repair, this review underscores its feasibility and calls for further research to fully harness its capabilities in civil engineering applications.

Keywords: UHMWPE; fiber-reinforced polymer; concrete repair; construction material innovation; sustainable design

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1. Introduction

The durability of existing buildings faces a challenge from constant wear and tear damage caused by external loading, inevitably leading to the formation and propagation of cracks on the concrete surfaces of structural components [1,2]. Excessive cracking increases the possibility of structural damage, making innovative solutions for repair and reinforcement necessary [3–8]. Traditional repair methods are limited in their ability to meet the requirements of modern engineering practices, prompting the search for novel approaches to address the challenges posed by deteriorating concrete [9–13].

Fiber-reinforced polymers (FRPs) have emerged as promising alternatives to conventional materials like steel plates for concrete repair and strengthening [14–16]. FRPs offer high strength [17], light weight [18], excellent corrosion resistance [19], ease of construction [20], and other advantages. Due to their high flexibility and low density, they incur low transportation costs and can wrap to any shape of structural components without adding extra weight [21,22]. Additionally, steel corrosion has long been a significant problem affecting concrete durability, and the maintenance costs associated with corrosion are also high [23]. The superior corrosion resistance of FRPs makes them increasingly attractive for use in civil engineering applications [24].

Among the various types of FRPs, Ultra-High Molecular Weight Polyethylene (UHMWPE) stands out for its exceptional properties and potential in concrete repair [25–28]. UHMWPE is a polymer formed from a large number of repeated ethylene units [26,29,30], characterized by its high tensile strength [31], elongation [32], good wear resistance [33], and energy absorption capabilities [34]. Traditionally used in applications such as joint replacements and bulletproof vests, the unique chemical and physical properties of UHMWPE make it an appealing choice for structural applications [35,36].

Recent advancements in manufacturing methods have further enhanced the properties of UHMWPE, making it more suitable for a wide range of applications, including concrete repair. Techniques such as crosslinking [37], blending with nanoparticles [38], and surface modifications [39] have significantly improved its wear resistance, strength, and compatibility with other materials [40].

In comparison to other FRP materials like carbon [41], glass [42], and aramid fibers [43], UHMWPE demonstrates promising advantages in terms of lighter density, larger elongation, higher strength, and modulus. Its excellent strain-hardening capacity makes strong energy absorption [44,45]. In contrast, other FRP materials are susceptible to detachment and breakage from concrete matrix under high-displacement dynamic loads, such as earthquakes [46–50].

Although the research on material properties and modification techniques of UHMWPE has shown promising results, there remain significant gaps and limitations in understanding its full potential for concrete repair. Further exploration and validation of UHMWPE for real-world engineering activities are needed. This review aims to provide a more in-depth exploration of the feasibility and potential of UHMWPE for concrete repair, highlighting its advantages, challenges, and areas for future research.

2. Material Properties of UHMWPE

In the late 1970s, the Dutch company DSM utilized white powdered UHMWPE as raw material and employed new gel-spinning-and-super-drawing technology to produce UHMWPE fiber [51–55]. The product, named "High Strength and High Modulus Polyethylene Fibre", propelled the chemical fiber industry into a new era [56,57]. UHMWPE fiber boasts excellent mechanical properties, including a great strength-to-weight ratio [58,59], high modulus [60], and good wear resistance [61,62]. Its unique molecular structure, consisting of long polymer chains, contributes to its high chemical stability and biocompatibility [60,62].

2.1. Molecular Structure

The molecular structure of UHMWPE explains the intrinsic advantages over normal polyethylene (PE) [63–67]. It is a unique polymer with a complex hierarchical structure that consists of large and medium-sized macropores, mesopores, and lamellar crystals [68,69]. Lermontov et al. [68] presented a method for increasing the crystallinity and specific surface area of UHMWPE, thereby improving its mechanical properties. This difference in crystallinity is also reflected in the physical appearance of UHMWPE, which has a rougher surface compared to HDPE [70]. The ideal structure of a polymer with high strength and modulus is an infinitely long macromolecular chain containing only a crystallized chain [71]. In contrast, macromolecular normal polyethylene with low molecular weight is amorphous and disorganized, as shown in Figure 1a. Therefore, UHMWPE utilizes high-molecular-weight polymers to significantly reduce the density of entanglement points between macromolecules [72], as shown in Figure 1b.

(**a**) (**b**)

Figure 1. Micro-structure of fiber, (**a**) normal polyethylene with low molecular orientation, (**b**) Ultra-High Molecular Weight Polyethylene Fiber [73].

2.2. Chemical Structure

The chemical structure of UHMWPE is a polymer formed from a very large number of repeated ethylene (C_2H_4) units, as shown in Figure 2. According to Ohta [72], PE has the strongest ultimate strength among polymers, pointing the way for developing PE material properties, as shown in Table 1. Compared to conventional high-density polyethylene (HDPE), UHMWPE exhibits higher crystallinity and molecular weight, resulting in a highly oriented and nearly straight-chain crystal structure [74,75]. These characteristics contribute to its superior mechanical properties.

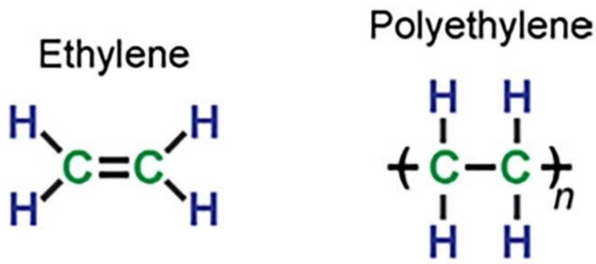


Figure 2. Schematic of the chemical structures of ethylene and polyethylene [62].

Table 1. Ultimate polymer strength of various polymers [72].

Polymer	Density (g/cm^3)	Molecular Area (nm^2)	Ultimate Strength (g/dyne)	Strength of Commercial Fiber (g/dyne)
PE	0.96	0.193	372	9.0
Ny-6	1.14	0.192	316	9.5
POM	1.41	0.185	264	-
PVA	1.28	0.228	236	9.5
Kevlar	1.43	0.205	235	25.0
PET	1.37	0.217	232	9.5
PP	0.91	0.348	218	9.0
PVC	1.39	0.294	169	4.0
Rayon	1.50	0.346	133	5.2
PMMA	1.19	0.667	87	-

2.3. Chemical and Physical Properties

Better physical properties of UHMWPE fiber depend on higher molecular weight and long-chain crystallization. Ultra-high molecular weight diminishes the amorphous regions between chain termini, augments intermolecular attraction, and engenders a higher abundance of crystalline phases characterized by favorable mechanical properties [76–79]. Molecules arranged in elongated chains demonstrate a consistent capacity for energy absorption, thus reducing vulnerability to damage and facilitating the optimization of their mechanical properties [78–83]. According to a previous investigation [62], UHMWPE has better ultimate tensile strength and impact strength than HDPE. In the research of Edidin and Kurtz [84], the wear rate of UHMWPE is a quarter of that observed in HDPE. Chang et al. [85] developed a specially designed tester to determine the effects of load intensity and loading speed on the friction coefficient of UHMWPE. Their findings revealed that the wear resistance of UHMWPE with composite texture surpassed that of other textures. The friction coefficient has a relation to interface molecular orientation [86–88]. As interface molecules are arranged in order, the sliding resistance becomes low, leading to a small friction coefficient. Therefore, UHMWPE has better wear resistance [89]. The chemical structure of UHMWPE is a simple linear homopolymer, composed solely of covalent bonds without any polar groups. Consequently, it exhibits negligible susceptibility to hydrolysis. The wide application of UHMWPE in the medical field demonstrates its exceptional chemical stability and biocompatibility [90].

3. Advancements in Manufacturing Methods of UHMWPE

Over the last few decades, significant research efforts have been directed toward enhancing the mechanical and chemical advantages of UHMWPE. Hussain et al. [8] reviewed three strengthening methods, including crosslinking, doping with nanoparticles, and surface modification.

3.1. Crosslinking Techniques

Crosslinking in UHMWPE causes the formation of chemical bonds between polymer chains, creating a three-dimensional network structure [91]. This configuration enhances the presence of double bonds within both the amorphous and crystalline phases, resulting in elevated levels of tensile strength, hardness, and chemical resistance [40]. This improvement can be attained through various means, including the application of silane (SiH_4) [91], chemical methods utilizing peroxides [92], and irradiation techniques [93]. Irradiation stands out as the most prevalent and efficient method for crosslinking UHMWPE among the above available techniques. The interaction of high-energy radiation causes the scission of C–C and C–H bonds, resulting in hydrogen radicals (H•) and alkyl macroradicals. These secondary macroradicals undergo chemical reactions, eliminating hydrogen via intra- or intermolecular mechanisms. The trans-vinylene formed from intramolecular mechanisms reacts with macroradicals to form Y-shaped crosslinks, while the chemical combination of two macroradicals creates an H-shaped crosslink, as shown in Figure 3.

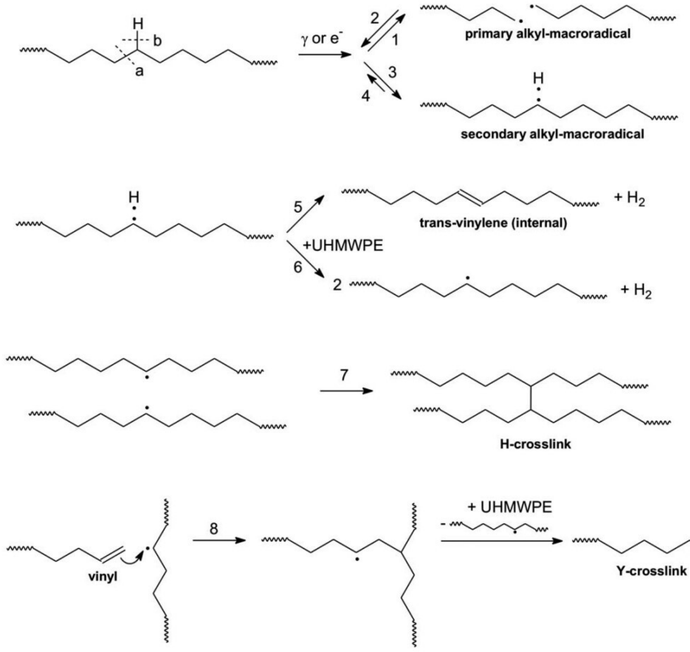
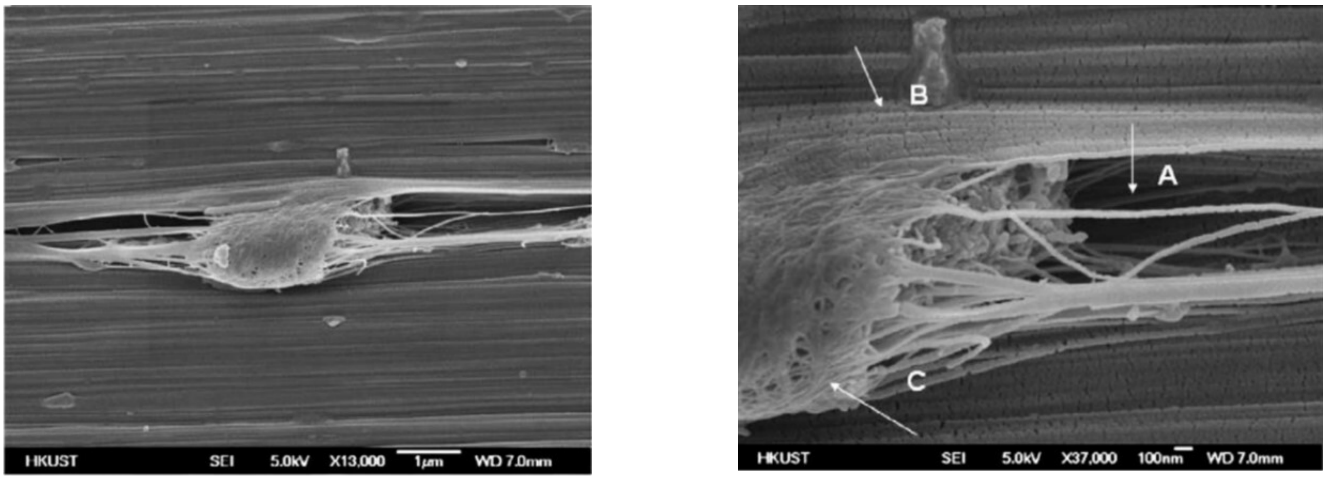


Figure 3. Chemical and molecular interaction of crosslinking UHMWPE under high energy radiation [94].

3.2. Doping with Nanoparticles

Blending with other materials is also an important method to develop UHMWPE material properties. Adding particle or fiber reinforcement can increase surface microhardness, thereby improving the abrasion resistance of the UHMWPE. In past literature, many reinforcing materials have been applied to enhance the wear performance of the UHMWPE matrix, such as zeolite [95], organoclay [96], zirconium particles [97], and others. Compared to the aforementioned materials, the incorporation of nanoparticles represents a superior alternative for enhancing mechanical and thermal properties [98]. Their small size results in a large specific surface area, enabling greater interaction with the matrix material. This higher surface area-to-volume ratio enhances the mechanical and thermal characteristics of composites [99]. UHMWPE is recognized as a superior thermoplastic material due to its high strength, high modulus, good wear resistance, high chemical stability, and biocompatibility. It holds significant potential for applications in various engineering fields. Consequently, numerous researchers have attempted to enhance its mechanical properties through the incorporation of nanoparticles. The reason for this improvement is the filling of polymer voids, creating a denser composite that is stronger than pure UHMWPE (with pores and voids) [100]. Ruan and Bao [101] found that the application of carbon nanotubes and carbon fibers on the surface of UHMWPE can enhance compressive strength. With the incorporation of carbon nanotubes (CNTs), the strain-hardening effects of UHMWPE are stronger during production. Crystallinity increased by 15%, and strength and modulus improved by 62% and 114%, respectively [102]. From the viewpoint of scanning electron micrographs, CNTs can form a strong combination with UHMWPE fibers during hot drawing, as shown in Figure 4. The tubular structure of CNTs distributes internal stress effectively, enhancing the mechanical properties of UHMWPE fibers uniformly.



(**a**) (**b**)

Figure 4. High-resolution scanning electron micrograph with (**a**) global view of carbon nanotubes on UHMWPE and (**b**) detailed view of fibers pulled from CNT clusters [103].

3.3. Surface Modification

The lack of strong adhesion to the matrix hinders the further development of UHMWPE, so surface modification of UHMWPE fibers can improve their interfacial bonding properties. The modification methods are generally divided into two categories, “wet” chemical techniques and “dry” modification [104]. Dry modification refers to modification methods that do not involve chemical solutions, including plasma treatment, corona treatment, and irradiation. The surface of UHMWPE can be modified by argon plasma fields [105–111]. Huang et al. [108] modified the surface of UHMWPE by argon plasma treatment at different treatment times, as shown in Figure 5. Figure 5a–d depict the microscopic view of the UHMWPE surface under 3000× magnification after 0, 1, 3, and 5 h of treatment under 40 W of plasma power, respectively. Increasing plasma treatment time can create more microcracks, resulting in greater roughness to improve adhesive strength. Bahramian et al. [112] found that the corona-treated UHMWPE had greater surface hardness than the pure form. The irradiation techniques not only belong to crosslinking but also surface modification.

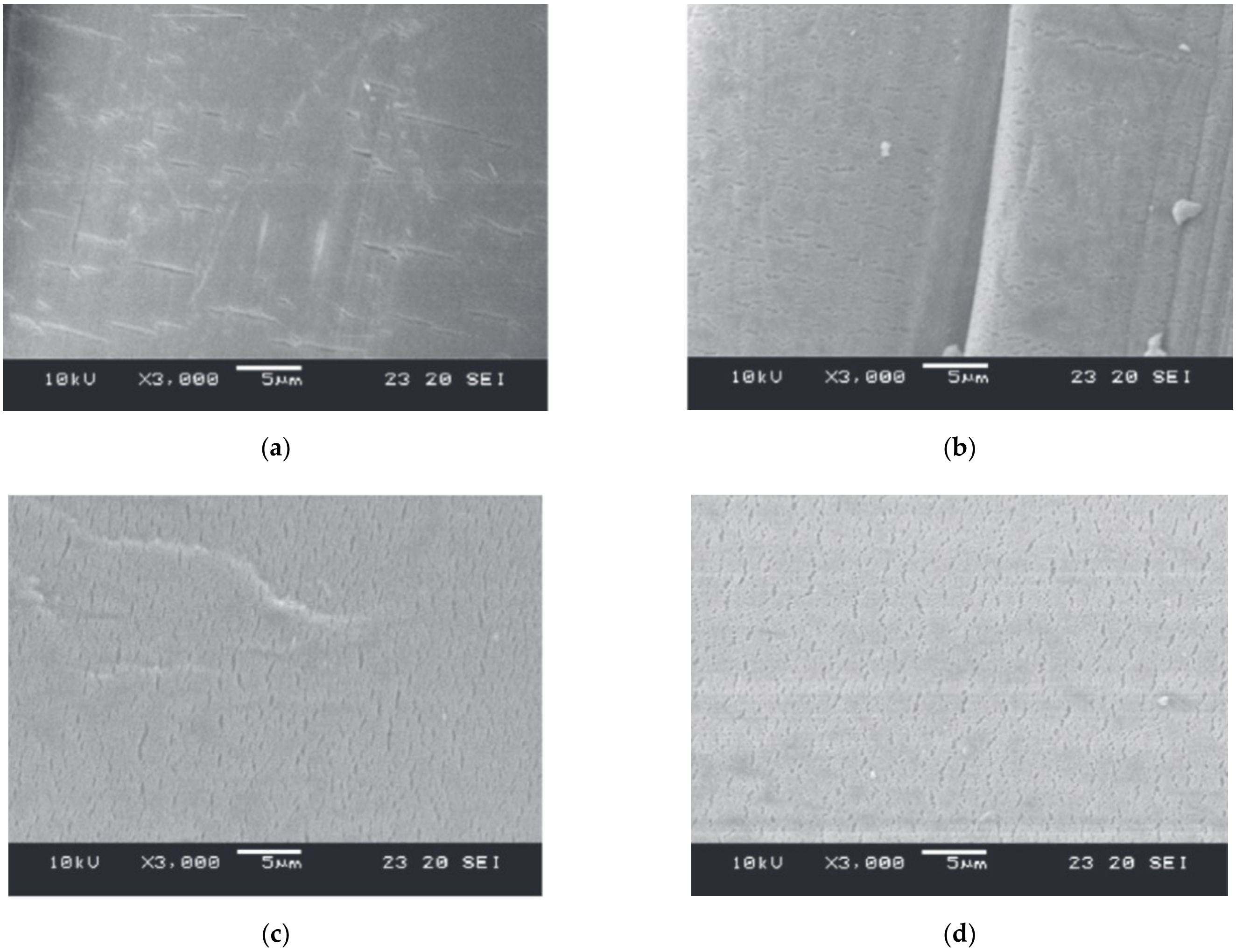
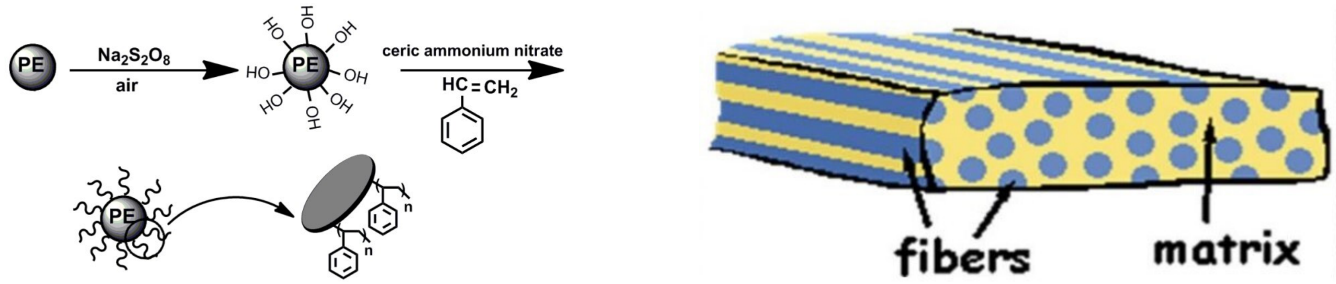


Figure 5. Surface morphology of UHMWPE after different argon plasma treatment times of (**a**) 0 h, (**b**) 1 h, (**c**) 3 h, (**d**) 5 h [108].

The wet chemical techniques are widespread due to their simple and convenient operation, including chemical etching [113], chemical grafting [114], and coating [110]. After soaking UHMWPE in modified acid and combining it with epoxy, the resulting composite material exhibits higher strength, modulus, and bending properties [115]. Sherazi et al. [116] successfully chemically grafted styrene onto the surface of UHMWPE to improve surface adhesion and enhance coating adhesion, as shown in Figure 6a. After applying a polydopamine (PDA) coating to the surface of UHMWPE, the fiber/matrix bonding strength can increase by approximately 42.50% compared to conventional composite materials [117].

In summary, these modification techniques aim to utilize active electrons or ions to break the covalent bonds on the UHMWPE surface, such as C-C and C-H bonds, to generate more free radicals [118], reduce chemical inertness, and achieve better interlocking with the matrix, as shown in Figure 6b. With the help of the above-mentioned strengthening techniques, UHMWPE can be developed into a strong potential FRP composite for strengthening and repairing concrete materials.



(**a**) (**b**)

Figure 6. Schematic diagram of (**a**) polystyrene on UHMWPE powder [116] and (**b**) schematic diagram of FRPs [110].

4. Comparative Analysis of UHMWPE with Other FRPs

In most country codes, the lifespan of residential buildings is 50 years [119,120]. With the development of urbanization in China over the last century, an increasing number of concrete structures currently require maintenance and strengthening. Nowadays, common methods for strengthening concrete include enlarging concrete sections [121], near-surface embedded reinforcement [122], and externally bonded reinforcement [123]. Increasing the cross-sectional area of concrete elements can reduce external stress to below the ultimate strength of concrete, but the self-weight of concrete is heavy and can diminish available room space [124]. Near-surface embedded reinforcement can overcome the disadvantage of loss of room space and heavy weight. However, grooving the concrete surface results in high labor costs, and the external steel rebars are susceptible to corrosion [125]. Regarding externally bonded reinforcement, both steel plates [126] and fiber-reinforced polymers (FRPs) [127] are commonly utilized.

4.1. Comparative Analysis of Physical Properties

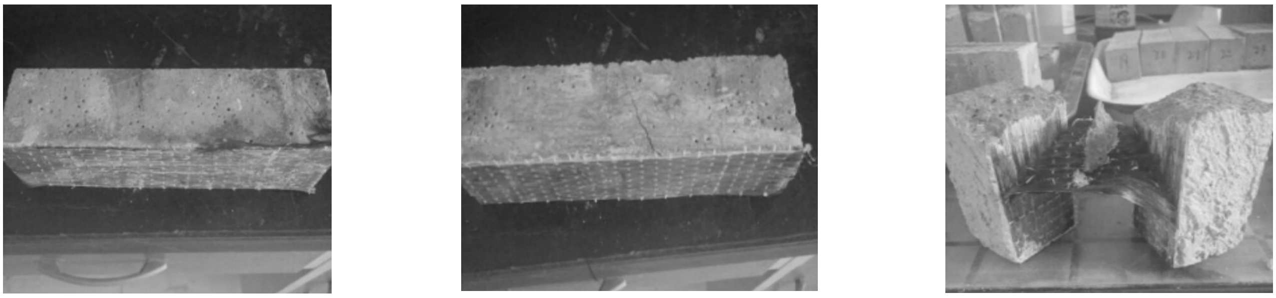
Fiber-reinforced polymers (FRPs) are premium materials for strengthening concrete. Due to their flexibility, they can wrap around any shape of structural components and have a high strength-to-weight ratio compared to steel plates. High-strength and high-modulus fiber is desirable for FRPs. Currently, carbon FRPs and glass FRPs are two popular materials for reinforced concrete. The modulus of carbon and glass fibers is 80 to 90 GPa and more than 200 GPa, respectively [128]. The tensile strength of both fibers is approximately 3 GPa [129]. Moreover, there are also many synthetic fibers, such as aramid, polypropylene (PP), polyethylene (PE), and polyvinyl alcohol (PVA) [130]. In Table 2, the mechanical properties of PVA are higher than those of PP and PE, yet the price of PE does not offer any advantage. However, the density of PE/UHMWPE is lighter than that of PVA. Therefore, at the same weight, the quantity of PE is greater than that of PVA, which helps to compensate for the higher price. Additionally, despite the weaker mechanical properties of PE, UHMWPE exhibits greater strength and modulus than PP and PVA. Therefore, UHMWPE is a polymer material developed based on PE with more powerful material properties, a unique molecular structure, and a stable chemical structure. Compared with popular reinforcement materials aramid and carbon fiber, UHMWPE has the characteristics of lighter density, larger elongation, and higher strength. Carbon-fiber-reinforced polymer (CFRP), the most common FRP used for concrete repair, has only a 1.04% rupture strain, resulting in a limited elongation capacity. In contrast, UHMWPE fiber can achieve an elongation of 3.5–3.7%, making it a better candidate for energy absorption if substituted for carbon fiber. Therefore, the remarkable material properties of UHMWPE make it a highly desirable choice for a wide range of engineering applications.

Table 2. Physical/mechanical properties and cost of fibers/FRPs.

Fiber/FRP Type	Specific Gravity (kg/m^3)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Elongation (%)	Approx. Cost (USD/kg)
Polypropylene (PP) [131]	910	1.5–12	240–900	-	1–2.5
Polyethylene (PE) [131]	920–960	5–100	80–600	-	2–20
Polyvinyl alcohol (PVA) [131]	1290–1300	20–42.8	1000–1600	-	1–15
Ultra-High Molecular Weight Polyethylene (UHMWPE) [110,132]	970–980	91–140	3700–4000	3.5–3.7	Around 2.477
Steel [131]	7840	200	500–2000	-	1–8
Kevlar [110,133–136]	1430–1440	55–143	3600	1.5–2.8	-
Carbon [110,137–147]	1500–1800	255–395	2300–3490	1.5–1.8	5–70
CFRP [148]	-	191	1990	1.04 (rupture strain)	-

4.2. Other FRP Application in Concrete Repair

The use of FRPs in concrete structures has been extensively studied. Soudki and Alkhrdaji [149] highlighted the effectiveness of externally bonded FRP systems for strengthening various concrete elements. In order to examine the strengthening effects of FRPs on concrete mechanical performance, experimental tests on small-size concrete specimens were started. Chen et al. [150] investigated the flexural strength of a 40 mm × 40 mm × 160 mm concrete specimen strengthened with carbon FRPs and glass FRPs, as shown in Figure 7. Munir et al. [151] presented the bonding strength between FRPs and the concrete matrix in different pastes. Li et al. [152] demonstrated the cracking propagation in small-sized concrete specimens. The development of load-bearing capacity is a significant concern after wrapping FRP cloth around concrete elements [153–155]. Campione [156] conducted compressive experiments on concrete prisms wrapped with carbon FRP cloth. Compared with plain concrete, the specimens with FRP cloth demonstrated increased toughness and higher ultimate strength due to their superior transverse strain capacity, as shown in Figure 8. Wrapping FRP cloth can improve the overall compressive behavior of concrete specimens while maintaining the integrity of the concrete [157]. Therefore, it is widely adopted to use FRP cloth to reinforce columns, as they are the most important structural components transferring load to the foundation. The axial bearing capacity of reinforced square columns with carbon or glass FRPs increased by at least 30%, with some experiencing increases of more than 85% [158]. In the case of fire-damaged columns, the load-bearing capacity can be restored to 71–116% of the original value with the help of FRP wrapping [159]. Additionally, the shear and flexural performance of existing concrete beams can be strengthened by repairing them with FRP materials [160]. When subjected to the same deflection as the original concrete, beams reinforced with CFRP did not fail completely [161]. It was found that FRP wrapping enabled a larger ductile behavior of strengthened beams. Furthermore, a significant improvement in the flexural capacity of concrete beam–column joints was demonstrated [162]. Mohammed [163] investigated the shear behavior and different failure modes of concrete beams retrofitted with CFRP. Compared with beams without CFRP, the ultimate load values demonstrated a 70% increment, while deflection decreased by 39%. This difference may be attributed to the properties of the FRP material. If UHMWPE is applied, concrete beam deflection could be further improved due to its stronger elongation capacity and higher energy absorption.



(**a**) (**b**) (**c**)

Figure 7. Small-size concrete specimen (40 mm × 40 mm × 160 mm) for flexural test: (**a**) initial photo of experimental specimen, (**b**) its crack pattern, and (**c**) failure mode [150].

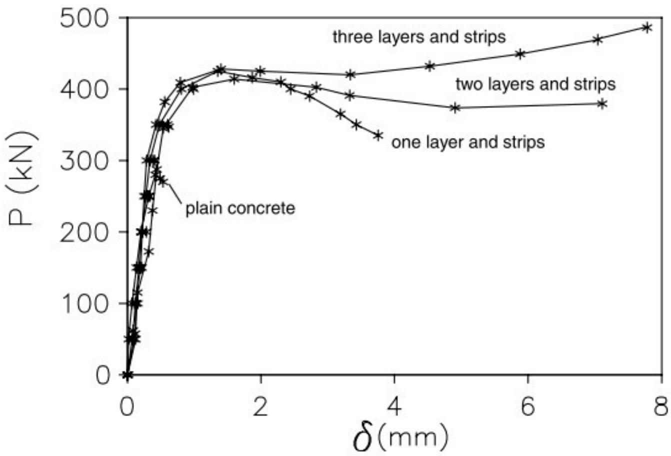


Figure 8. Load-shortening curves for wrapped specimens with different layers of CFRP [156].

4.3. Advantages of UHMWPE over Other FRPs

UHMWPE, with its superior tensile strength, elongation, and energy absorption capabilities, has been extensively studied for its application in strengthening concrete structures. Li [164] proposed that high tensile strain capacity was one of the most significant properties of ductile repair materials. UHMWPE, with its high toughness and impressive strength-to-weight ratio, has become widely utilized in both the military and medical industries [165,166]. Therefore, the high tensile strain capacity of UHMWPE has the potential to enhance the strength and durability of building structures. Sun et al. [167] demonstrated that UHMWPE can significantly enhance the flexural strength and toughness of cementitious composites. Lv et al. [168] presented a type of engineered cementitious composites (ECCs) mixed with UHMWPE fibers as a coating for concrete repair. The tensile strength and strain-hardening capacity were developed, and good compatibility was found between the UHMWPE fibers and the cement matrix. Tinoco and de Andrade Silva [169] investigated strain-hardening cementitious composites (SHCCs) mixed with different fibers as a repairing coat. They compared the mechanical properties of adding PVA, UHMWPE, and steel fibers. In both uniaxial tension and beam bending tests, the UHMWPE fiber groups demonstrated structural performance similar to those of the PVA and steel fiber groups. In the UHMWPE SHCC coating group (RB-1 and RB-5), the plateau observed in the F-D curve indicated its exceptional strain-hardening capability and toughness, unlike the concrete beams repaired with SHCC mixed PVA (RB-3 and RB-6), which exhibited a rapid decrease in load-bearing capacity upon reaching the failure point, as shown in Figure 9. Therefore, it is possible for UHMWPE to replace some common fibers for reinforcing concrete specimens. Some studies have shown that, in concrete canvas structures, the tensile strength and flexural strength of CNT-modified UHMWPE are 3 to 3.8 times greater than those of ordinary fabrics [25,164]. Due to its unique macromolecular structure, UHMWPE has a low density but high modulus, which allows it to exhibit mechanical properties comparable to those of metals or ceramics [170]. Additionally, it possesses the ability to absorb energy and offers high toughness. In contrast, materials like glass or carbon FRPs, commonly used in the market, are susceptible to detachment and breakage under high-displacement dynamic loads, such as earthquakes [171]. Although UHMWPE displays poor high-temperature resistance and may melt quickly in the event of a fire, the polymer matrix on the fiber also loses its bonding properties. Hence, its poor heat resistance has little impact on the external repair of concrete [172]. It belongs to effective ductile repair materials, resistant to brittle damage, leading to extended service life, thereby minimizing raw material consumption and yielding greater environmental benefits [173]. Therefore, UHMWPE can make a greater contribution to the repair of civil buildings compared to other FRPs, considering criteria such as durability, cost-effectiveness, strength-to-weight ratio, structural performance, and environmental benefits.

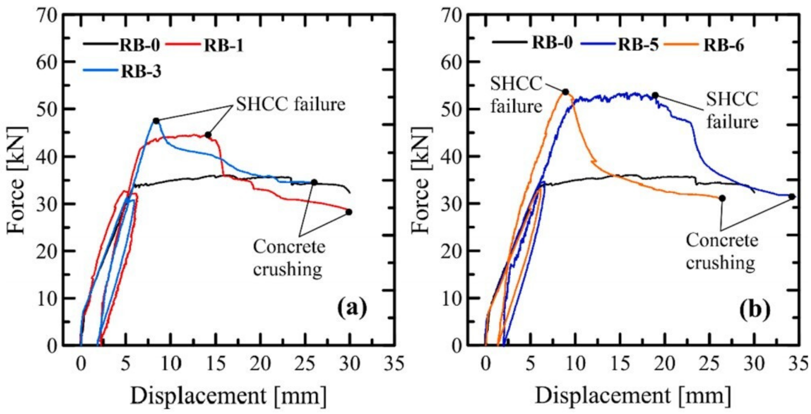


Figure 9. Load-displacement curves obtained in the structural tests: (**a**,**b**) represent different mixing proportions of cementitious composites, reinforced with UHMWPE/PVA and steel fiber [169].

5. Resent Research and Application of UHMWPE in Concrete Repair

5.1. The Application Research of Other FRPs

In recent research, FRPs have been popularly applied in concrete repair. FRP is composed of two main components: one is a strength material, mainly derived from fibers, and the other is a polymer matrix material used to bond and protect fibers [174]. Currently, the types of popular fibers used in concrete repair are glass, carbon, and aramid [175]. Basalt FRPs have only been tried for retrofitting concrete structures in the past decade [176]. The most common matrix materials are thermosetting polymers, such as epoxy resin [177], polyester [178], and vinyl ester [179]. In most experiments and real construction, FRPs adhere to concrete surfaces by epoxy resin, which offers greater mechanical properties and durability [180]. FRPs, with their excellent characteristics, have been widely applied in strengthening vulnerable concrete components, wrapping columns to enhance compressive strength, and wrapping beams to improve flexural and shear performance. Thomsen et al. [181] categorized the failure modes of FRPs on concrete into two categories: combination destruction and non-combination damage. Combination failure involves concrete crushing and FRP rupture, while non-combination failure consists of debonding, which is brittle and prevents the full utilization of the physical capacity of concrete or FRPs [182]. Therefore, the selection of an appropriate adhesive between concrete and FRPs is crucial.

The most important function of interfacial adhesives is to transfer stress. Because epoxy resin shares the same chemical components as the matrix of composites, it remains the most popular adhesive for repairing concrete with FRPs [183–187]. Both materials possess polar groups capable of attracting each other, thus creating a strong intermolecular force that leads to excellent chemical stability. Additionally, epoxy can serve as a liquid adhesive, capable of covering and penetrating uneven surfaces or pores in solid materials. Consequently, epoxy resin stands out as the most commonly used adhesive [180]. Li et al. [188] proposed a kind of modified epoxy resin adhesive (MER), with larger tensile strength, tensile strain, elastic modulus, and flexural strength than neat adhesive. In contrast, Li et al. [189] found that epoxy resin could degrade in a high-temperature environment, due to its glass transition temperature of 120 °C. Chen et al. [150] proposed that some fillers of resin are toxic heavy metals that cause harmful effects on health and the environment. To improve those weaknesses, another green and economical repair material was proposed, magnesium phosphate cement (MPC). According to Kejia [190], MPC can create a good bonding result in the repair of damaged concrete structures. The best water–cement ratio and the content of fly ash were determined, 0.30 and 30%, respectively [150]. The effects of calcination temperature, water–cement ratio, and mixing mass ratio on the MPC strength by bending, splitting, compression, and bearing experiments were investigated by Xing and Wu [191]. The calcination temperature of 1100 °C, the mass ratio of 2:1, and the water–cement ratio of 0.2 can lead to the best performance of cement strength based on their experiments. The effect of fly ash on MPC was demonstrated by Liu [192]. The bonding strength of MPC was also temperature-dependent [193]. Around 130 °C of the surrounding environment, approximately 50% of residual compressive strength was lost. The amplitude of strength decreased slowly after 130 °C. Furthermore, MPC and resin need to be compared more in future research.

However, the primary failure mode usually involves FRPs peeling from the concrete surface after long-term use [194,195]. With the development of time, FRP-concrete structure will age, potentially leading to a change in main failure mode. The brittle adhesive decohesion possibly happened because the adhesives between FRP and concrete cannot ensure long-term effectiveness. Many researchers have examined the influencing factors on its durability. Various external environmental factors can affect the bonding quality of adhesives, such as temperature [189], moisture [196], external cyclic loading [197], and ultraviolet radiation [198], as shown in Figure 10. In recent research, most investigations about FRP durability have been presented based on experiments simulating harsh conditions [198]. The impact of temperature and moisture on concrete specimens will result in some microcracks and increased absorption of water molecules, leading to significant plasticization and hydrolysis. The chemical bonds between the concrete substrate and FRPs will break [182,199].

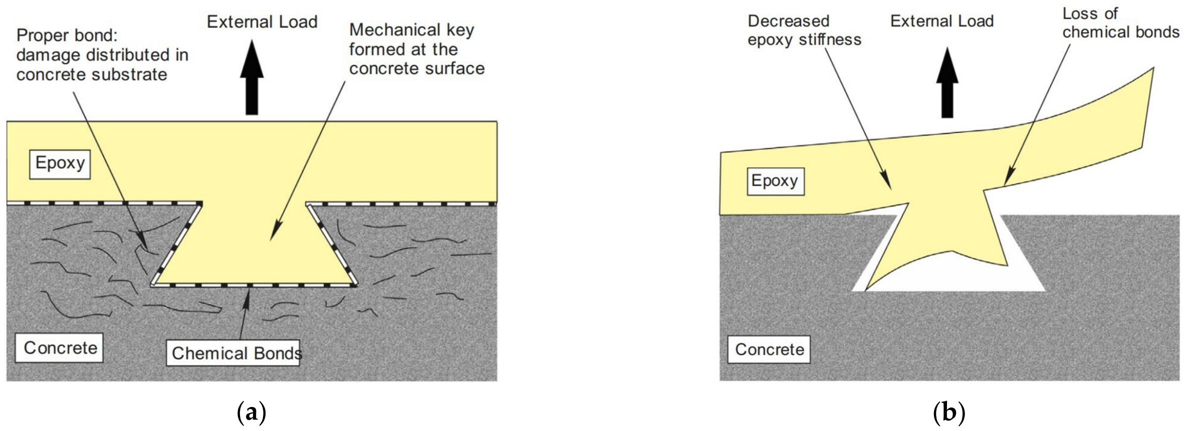


Figure 10. Failure mode of epoxy–concrete bond: (**a**) in dry ambient conditions; (**b**) following exposure to moisture [196].

5.2. The Application of UHMWPE in Concrete Repair

The application of UHMWPE in concrete repair is a topic of interest due to its potential to enhance the mechanical properties of concrete. Many researchers explored the use of UHMWPE in concrete and found that it can improve the workability, strength, and durability of the concrete [200–204]. Osman et al. [205] demonstrated that fiber concrete reinforced with UHMWPE had better flexural behavior than that reinforced with PVA. Tinoco and de Andrade Silva [169] mixed UHMWPE into ECC coating on concrete beams, resulting in a

50% increase in bending strength. Compared with ECC coating, externally bonded FRPs are a kind of "dry" repairing technique. Formwork maintenance and waiting hardening processes of cementitious composites are unnecessary, as the construction can be completed by directly affixing FRP cloth to the areas requiring reinforcement. Czarnecki [206] discussed the role of polymers in concrete repair, emphasizing their importance in enhancing adhesion and shortening the time to readiness for use.

However, there is limited research that investigates UHMWPE application in concrete repair. In future research, UHMWPE can be investigated and compared with carbon, glass, and aramid FRPs for concrete repair. In addition to assessing the physical strength properties, it is imperative to evaluate and compare the durability of UHMWPE with other FRPs in external environments. UHMWPE has great physical and chemical properties, so applying it in concrete repair is feasible.

6. Conclusions

The utilization of UHMWPE in concrete repair presents a promising approach to enhance the mechanical properties and durability of structures. Based on a comprehensive analysis of its molecular and chemical structure, as well as its application in comparison to other FRPs, it is clear that UHMWPE holds significant potential for revolutionizing concrete repair methods. Despite the promising properties of UHMWPE, there are still significant gaps in current research that await further investigation.

Limited research on the use of UHMWPE in concrete repair, especially compared to conventional FRP such as carbon, glass, and aramid fibers, has hindered understanding of its long-term performance and superiority. Further investigation is needed into its structural applications, reinforcement effects, and durability under diverse environmental conditions. Understanding the effects of factors such as temperature, moisture, cyclic loading, and UV radiation on the bond between UHMWPE and concrete substrates is crucial for ensuring its effectiveness. Exploring innovative modification techniques, including surface modification, nanoparticle doping, and crosslinking, can enhance the application-specific performance of UHMWPE. Demonstrating successful real-world applications through field trials and case studies will validate its effectiveness and provide insights for improvement.

In short, through concerted efforts in research, development, and practical implementation, UHMWPE has the potential to become another promising solution for strengthening and repairing concrete structures.

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