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Enhancing Concrete Strength with Polymer-Based Additives in the Cement Matrix: A Comprehensive Review

Sasan Kermani, [a,*] Soheil khalatbari [b]

[a] *Department of Civil Engineering, Nour Branch, Islamic Azad University (IAU), Nour, Iran*

[b] *Department of Civil Engineering, Ramsar Branch, Islamic Azad University (IAU), Ramsar, Iran*

ABSTRACT

The modern types of concrete consist of a mixture of aggregates, cement, water, and optional additives and admixtures. Polymer additives, such as superplasticizers, latexes, redispersible powders, polymer fibers, and recycled polymers, have shown promise in significantly altering the properties of concrete and mortar. These polymeric materials are widely used in the construction industry to enhance resistance to cracking and improve overall performance. This paper provides an overview of popular polymeric additives and their impact on concrete properties, as well as the relationship between the chemical structure of additives and the behavior of the resulting concrete.

ARTICLE INFO

Received: January 1, 2024
Accepted: March 8, 2024

Keywords:
Cement
additives
Superplasticizers
Polymer
Concrete additives
Redispersible powders

DOI: 10.61186/JCER.6.1.48
DOR: 20.1001.1.2538516.2024.6.1.6.5

1. Introduction

The cement industry, a major producer in terms of volume, supplies building materials for the construction industry. Cement is a key ingredient in concrete, the most widely used building material with diverse applications and primarily used for structural elements. The widespread use of concrete is due to factors such as abundant resources, low cost, and high compressive strength [1]. Concrete is a mixture of various substances serving different purposes, typically containing aggregates like gravel, sand, and/or stones, along with an adhesive usually made of cement and water (10–15% vol.). Different types of concrete exist, including high-performance concrete developed in the 1990s characterized by low water content due to the introduction of plasticizers and secondary binders. This type of concrete exhibits significantly increased compressive strength compared to standard-strength concrete [2]. The development of very tall buildings and large structures has led to increased requirements for concrete with features like high compressive strength and exceptional durability. To address these needs, lightweight concrete (LWC) was developed with a density ranging from about 1400 to 2000 kg/m3 due to inner voids in its

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[*] Corresponding author. Tel.: +989123355282; e-mail: s_68_kermani@yahoo.com.

structure [4]. Additionally, ternary and quaternary binder systems have been introduced using different cementitious materials to achieve early strength, rapid setting, and better shrinkage compensation than standard OPC-based materials [6]. Furthermore, research has focused on improving concrete mechanical properties through the addition of polymers to the cementitious matrix. Polymer-modified concrete (PMC) or polymer-modified mortar (PMM) involves various forms of polymers such as latexes, liquid resins, water-soluble polymers and copolymers, fibers, and re-dispersible powders that can enhance properties like flowability, setting time, freezing–thawing resistance, mechanical properties, anti-penetrability, microstructure change, shrinkage reduction effect [10-18]. Fibers have also been examined as additives incorporated into the cementitious matrix to improve tensile and flexural performance while reducing shrinkage cracking [20-28]. Synthetic fibers can be replaced with recycled polymer material as a sustainable solution for utilizing polymer waste as filler or modifier in concrete production [29-31]. This paper provides an overview of recent developments and research on polymer additives used in concrete-based composites. It focuses on how various polymer additives impact the parameters of mortar and concrete.

The review is specifically focused on superplasticizers, latexes, redispersible powders, admixtures for improved crack resistance, fibers, and recycled polymers as potential additives in concrete-based composites. It emphasizes the connection between the chemical composition of these additives and the overall behavior of concrete.

2. Plasticizers and Superplasticizers

The concrete industry experienced rapid development in the 1990s with the introduction of a new type of chemical admixture known as plasticizers. The initial generation was based on lignosulphonate compounds, which reduced the water/cement ratio by approximately 5–10% [32]. It is widely recognized that reducing the water content in mortar leads to a decrease in the overall porosity of concrete [16]. Consequently, decreasing the water amount in mortar has benefits for durability and workability, and also contributes to shrinkage reduction [33]. Fresh cement paste can generally be seen as a suspension dispersion with chemical reactivity. Upon exposure to water, the cement grains immediately begin to dissolve and hydrate, resulting in the accumulation of both positive and negative charges on the cement surface. As a result, electrostatic interactions between opposite charges on the surfaces of the grains lead to the flocculation of cement grains and subsequent water entrapment [34]. Water present in the mixture can be chemically bonded in hydrates, physically adsorbed on cement grain surfaces, entrapped in flocculated structures, or remain non-bonded as free water, serving as a dispersion medium. It is well established that macroscopic properties of liquid–solid dispersion, such as viscosity and flowability, are dependent on microstructure, which is closely linked to liquid–solid interface properties [35]. The addition of plasticizers or superplasticizers to the cementitious matrix brings about significant changes in solid–liquid interface properties (Figure 2) [36,37].

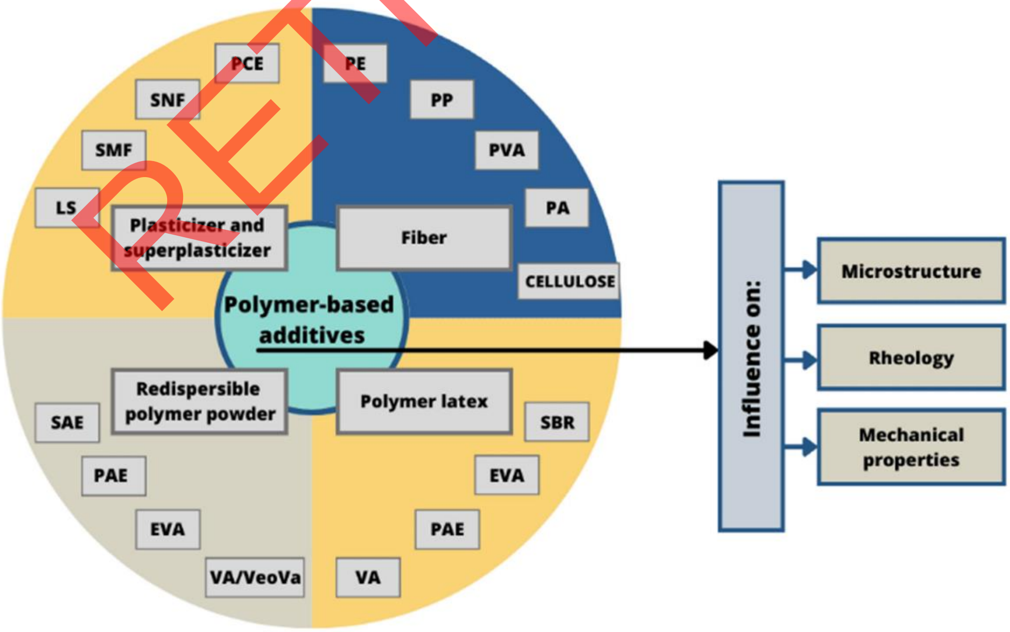

Figure 1. illustrates the types of additives and their impact on concrete-based composites.

A category of compounds that can reduce the water/cement ratio by approximately 25% is known as superplasticizers [38,39,40]. The introduction of these compounds has proven to be a convenient and practical method for enhancing the properties of concrete. However, the high fluidity they induce can lead to adverse effects such as bleeding and phase separation. To address these drawbacks of superplasticizers, the addition of viscosity-enhancing compounds was developed [41,42]. Superplasticizers come in various types with differing chemical structures and can be categorized into groups such as lignosulphonates, sulfonates, naphthenates, melamine sulfonates, and polycarboxylates [43]. Unlike plasticizers, superplasticizers operate through a different mechanism and consequently have varying effectiveness in reducing water mixing. The specifics of this mechanism are discussed later in this review. Different types of reactive groups present in the molecules of superplasticizers bond with Ca2+ cations at different strengths. According to published data, the strength of these bonds decreases in the following order: phosphate > carboxylate > sulfonate > sulfate > alkoxide and water [44]. Therefore, polycarboxylate containing -COO− groups demonstrates improved effectiveness in dispersing cement particles compared to plasticizers containing -SO3− groups, for example. Furthermore, research efforts have been made to investigate the efficiency of polymer admixtures containing the most effective groups for chelating calcium ions, such as phosphonates and phosphate groups [36,45,46].

J. Stecher and J. Plank synthesized a phosphated comb polymer superplasticizer, testing its dispersing performance in cement through slump tests in cement paste [45]. They found that polyphosphate superplasticizers exhibited improved dispersing performance compared to PCEs superplasticizers, with less retarding effect on cement. The authors emphasized that the high calcium complexing capacity of the phosphate group contributed to these results. Both plasticizers and superplasticizers are essential admixtures in concrete, listed in the European standard PN-EN 206 as a possible solution for achieving the right consistency by reducing water content, modifying consistency without changing water and cement amounts, or reducing cement content [52]. Superplasticizers, also known as high-range water reducers, are often used in concrete formulations to reduce water volume and achieve higher solid content while maintaining proper consistency. Scientists and engineers have identified basic properties of superplasticizers, confirming their ability to improve the workability of fresh concrete [53], chloride binding [54], and durability of cementitious materials [16]. However, using such compounds has introduced new challenges due to poor compatibility with the multi-component system of concrete, including cement, fine aggregate, and additional materials. Significant problems include bleeding, segregation, low initial slump, flash set, and set retardation [55]. Consequently, scientists have begun thorough investigations into the interactions between superplasticizers and particles in the cementitious matrix. N. Roussel et al. indicated that rheological properties of fresh concrete are determined by interactions among particles in the cementitious matrix. As the cement hydration process progresses, new rigid phases are created such as anhydrous phase at an early stage, ettringite, calcium silicate hydrate (CSH), and gypsum. This leads to increased yield stress, thixotropy, and hardening of the cementitious material significantly reducing workability [36,55]. The application of superplasticizer serves to keep distance among particles through distribution of polymer molecules adsorbed onto particle surfaces, decreasing interaction strength. Improved workability results from releasing a large quantity of water during deflocculation process [34,55]. Numerous studies have shown that fluidity of fresh cement paste depends on the amount of superplasticizer adsorbed by a square meter of solid particles [57-59]. The adsorption of superplasticizer on solid surface depends on polymer's chemical structure at solid interface and pore solution containing different dissolved ions [36]. It is important to note that processes of superplasticizer adsorption and cement hydration occur at a certain point during concrete formation [60]. At early stages during first period of cement hydration new phases develop leading to morphology changes in the cementitious matrix. Superplasticizers display different adsorption affinity toward surface of various hydration products and mineral phases affecting hydration process including ettringite formation. Therefore, hydration rate mortar morphology surface properties of hydration products their size and amount greatly influence concrete workability [61-63]. In case of Portland cement hydration main composition of solid surfaces is result of hydration calcium silicate aluminate phases among them certain interfaces can be specified separating ettringite gypsum CSH anhydrous phases. According to previous studies ettringite shows highest adsorption capacity for superplasticizers CSH phase adsorbs superplasticizers at least 3–10 times less than ettringite consequently ettringite is considered crucial phase for understanding fresh concrete rheology [36]. Marchon indicated that ettringite surface is entirely covered by polycarboxylate superplasticizer (PCE). Liu et al provided elucidatory description interaction between polycarboxylate polymer molecules and hydration products OPC surface coverage cement hydration products by PCE together with size distribution cement particles affects workability obtained material Polycarboxylate superplasticizer strongly adsorbs onto positively charged cement particles however adsorption process could be weakened through screening effect counterions The other recently analyzed super plasticizer is Welan gum In work by Khayat it was established that Welan gum at low shear rates is able increase yield stress enhance rebuilt-up kinetics rest increase viscosity cement paste It is noteworthy that Portland cement not only type used practice there also other types have different mineral composition H Tian investigated effects polycarboxylate superplasticizers sulfoaluminate SAC systems SAC contains calcium sulfoaluminate fraction various calcium sulphates such $CaSO_4$ $CaSO_4·2H_2O$ $CaSO_4·0$ $5H_2O$ responsible faster hydration SAC compared OPC article H Tian effects polycarboxylate superplasticizers obtained via radical copolymerization acrylic acid AA a-methallyl-x-hydroxy poly(ethylene glycol) monomer ratio 4 ordinary Portland investigated SAC system study confirms differences compatibility selected superplasticizer used The adsorption superplasticizer solid surface depends chemical structure polymer added superplasticizer adsorbed onto surface consequence electrostatic specific interaction interface Figure 3.

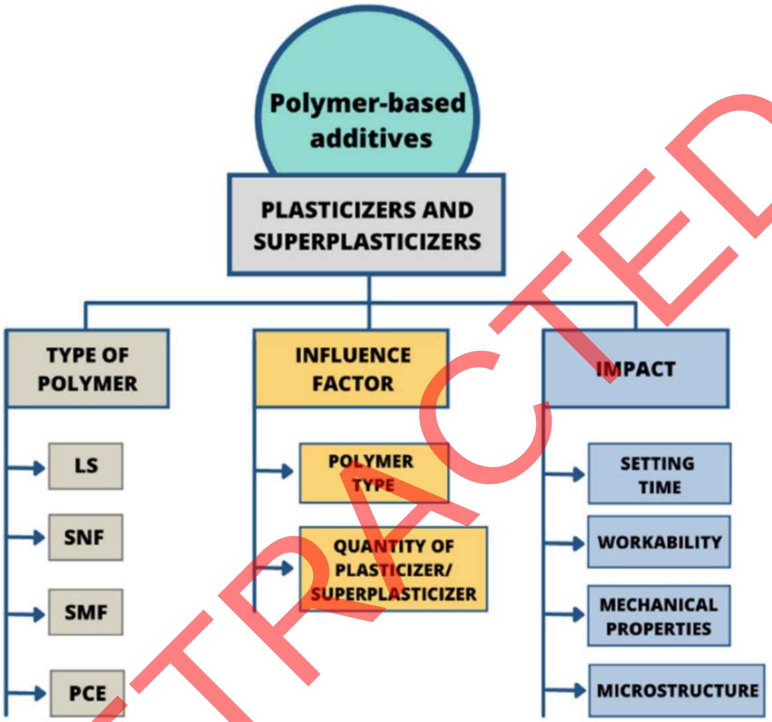

Figure 2. Diagram illustrating the different types of plasticizers and superplasticizers, factors that influence them, and the resulting changes in concrete-based composites.

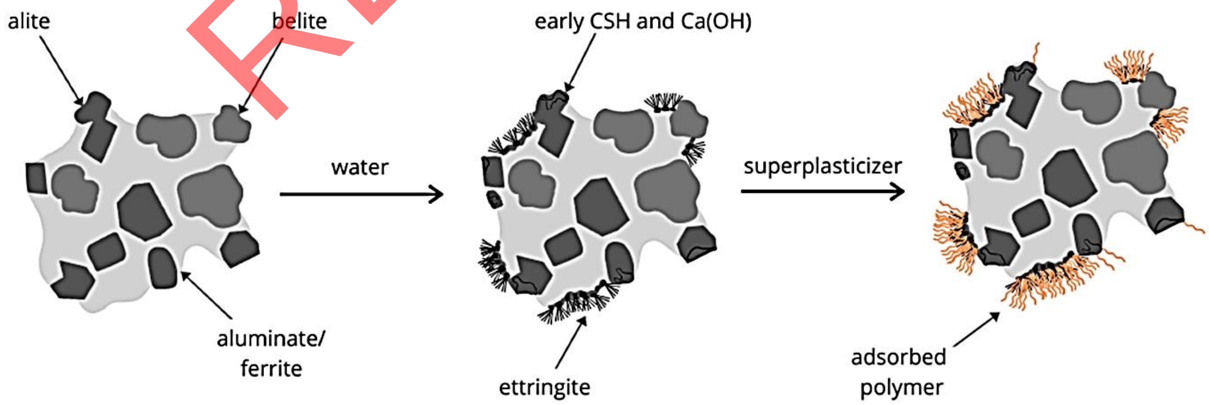

Figure 3. The diagram of a hydrating cement particle with non-uniform distribution of superplasticizer polymer on its surface (adapted from [67]).

It is widely acknowledged that the functional group of a superplasticizer has varying adsorption affinity towards a given surface. This was discussed by J. Stecher and J. Plank [45], who synthesized phosphate comb superplasticizers based on methacrylate ester and compared their properties with their carboxylate counterparts. They found that polyphosphate comb polymers outperform the polycarboxylate ones in terms of their dispersing capacity in cement paste, attach more readily to the cement surface, and impede cement hydration to a lesser degree [45]. In addition to the type of functional group of superplasticizers, other parameters of polymers significantly influence the adsorption process. These parameters include the number and density of the adsorbing groups, the length of the side-chain, as well as its grafting density [55,68]. Numerous studies indicate that the dispersing efficiency of PCE superplasticizer depends on either the dosage and quantity of PCE adsorbed on the surface of cement particles or the charge density and activity of the long side chain [69,70,71]. Furthermore, it has been noted that superplasticizers impact the setting time of fresh concrete and its mechanical properties. Polycarboxylate superplasticizers slow down ettringite formation but increase its total surface area [62]. It was found that PCE superplasticizers facilitate the formation of nano-sized ettringite, which is a primary source of incompatibility between cement and additives [61]. Moreover, PCE adsorbs onto reactive sites of $3CaO\cdot SiO_2$ (C_3S), inhibiting its dissolution and delaying the hydration process [64]. Shen et al. indicated that adding PCE to SAC could delay the setting time of cement-based substances [72]. Additionally, a superplasticizer can positively affect concrete's mechanical properties by improving microstructure, especially due to reducing water/cement ratio. Several studies have investigated how superplasticizers influence mechanical and rheological properties of mortar and concrete. Researchers have established that the effect of superplasticizers on hardened concrete performance depends on the type and dosage used as well as the binder [43,68,73]. M. Benaicha et al. presented a correlation between rheology and strength in self-compacting concrete (SCC), where compressive strength decreased with an increase in superplasticizer amount [70]. Superplasticizers act as dispersants in colloidal particle suspensions to prevent undesired agglomeration and reduce overall viscosity. To allow cement paste flow, it must exceed yield stress associated with rigid particle networks. The yield stress depends on colloidal and contact interactions among particles and nature of solid particles and their volume fraction [55]. Superplasticizers may interact with cement particles through different mechanisms directly related to their chemical structure. Generally, two mechanisms are distinguished: electrochemical forces and steric hindrance forces [74,75]. Figure 4 presents two different mechanisms of action for superplasticizers in the cementitious matrix.

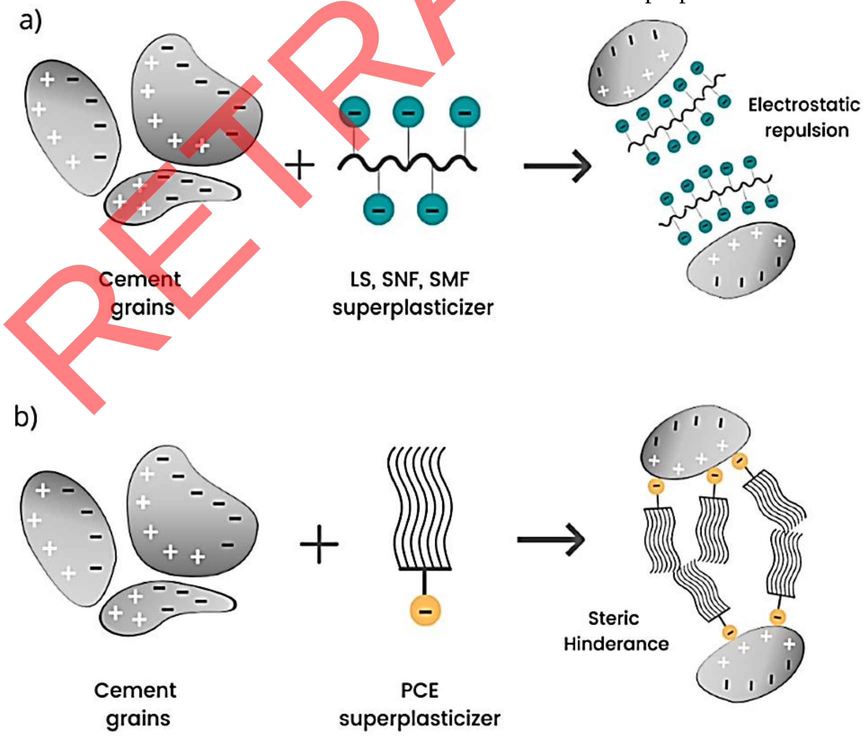

Figure 4. Diagram: (a) the impact of electrostatic repulsion on cement; (b) steric hindrance mechanism, adapted from [51].

The mechanism based on electrochemical forces was initially developed to explain the properties of plasticizers like lignosulphonate. Lignosulphonate compounds have a bipolar structure and exhibit typical polyelectrolyte properties. Their interaction mechanism is based on the physical repulsion of negatively charged cement particles, causing the disintegration of cement lumps into smaller particles, which reduces surface tension on the grains wetted by mixing water. Consequently, fine cement grains move more freely [47]. The electrostatic repulsion leads to an increase in the zeta potential, which depends on the presence of negative charges in the cementitious matrix [76,77]. Both naphthalene and melamine operate similarly to lignosulphonate plasticizers, providing an electrical dispersing effect [74]. In contrast to linear polycondensates that disperse cement particles through electrostatic repulsion, PCE molecules with comb-shaped structures achieve dispersion mainly through steric hindrance [46,65]. Generally, polycarboxylate-based superplasticizers, including polyacrylates, acrylic esters, and sulfonated polystyrene, consist of negatively charged backbone carboxylic groups and lateral grafted chains composed of ethylene oxide units (EOUs) [78]. The steric hindrance effect results from oriented adsorption of superplasticizer molecules on positively charged cement surfaces, weakening the attraction between cement particles. The negatively charged carboxylate anions at the polymer backbone adsorb onto positively charged surfaces of cement particles. Simultaneously, grafted side chains hinder aggregation of cement particles, introducing steric repulsion and a fluidizing effect. Upon adsorption of polycarboxylate superplasticizer, the particles' zeta potential changes from positive to negative or zero [75]. As a result of attaching superplasticizers to cement particles, they cannot approach each other and the attraction forces among them are weakened. Several studies have shown that mortar fluidity depends on the amount of superplasticizer adsorbed on particle surfaces [57,58]. A different perspective on superplasticizers and their interactions with cement has been presented in works by Flatt and Hust [79] and Flatt et al. [80]. According to their theory, introduced superplasticizer is divided into three parts. They have established that the first part is utilized during chemical reactions. The second part is adsorbed onto the cement surface while the last part constitutes the superplasticizer forming a saturated system after introduction of an adequate volume of additive. Moreover, according to Qian et al., it should be emphasized that an increase in PCE superplasticizer concentration leads to an increase in both the adsorbed part and remaining part of the additive.

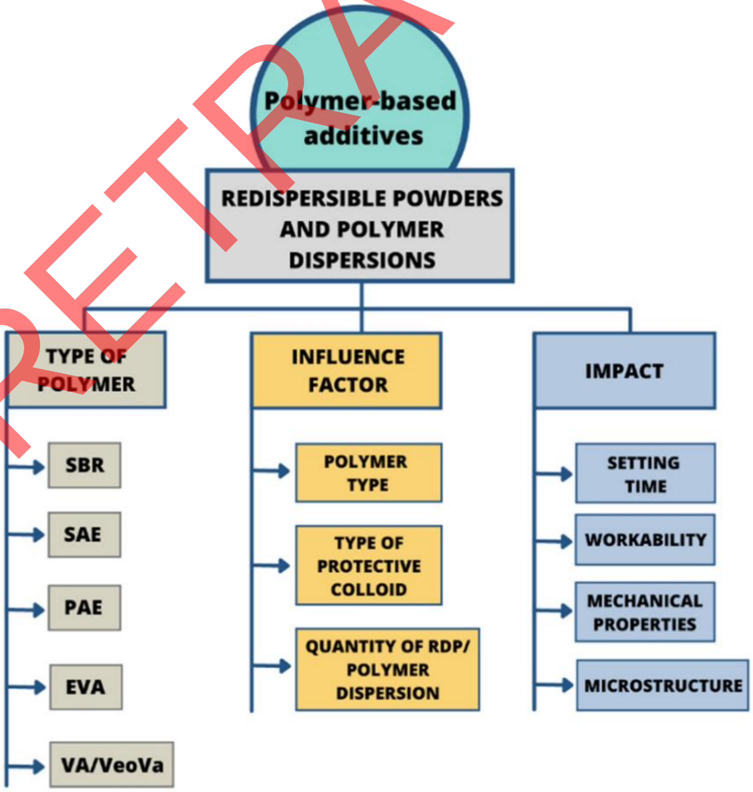

Figure 5. Diagram illustrating the impact factors and alterations induced in concrete-based composite by redispersible powders and polymer dispersion type.

3. Redispersible Powders and Polymer Dispersions

The rapid growth of the construction industry has led to efforts to enhance the fundamental properties of concrete and address its limitations, such as brittleness, low durability, and insufficient strain capacity, by modifying the microstructure of hydrated cement. In recent years, advancements in building construction have significantly progressed, and research on high-performance cement-based materials has been advanced to meet industry requirements. One way to improve concrete performance, including strength and durability, is by incorporating polymers into the cement matrix. Cement-polymer composites are formed by replacing all or part of the cement hydrate binder with polymers. Polymer-modified concrete was initially introduced in the 1990s and has since become a common construction material [10]. Today, various types and forms of polymers are used as chemical admixtures (Figure 5). Among these widely used additives are polymers with different chemical structures, such as lignosulfonates, polyvinyl acetate, ethylene-vinyl acetate, styrene-butadiene copolymers, styrene-acrylic, and polyacrylic ester [81,82]. Numerous studies have been conducted on these materials [12,83,84,85,86]. Currently, polymers are incorporated into cement in various forms, including latexes, liquid resins, redispersible powders, and water-soluble homo- or copolymers [81]. Given that the type of polymer used in the manufacturing process impacts the properties of the resulting composite, the selection of a polymer type and form depends on the intended use of concrete and is associated with desired properties such as strength, chemical resistance, and durability [87].

Initially, polymer-modified mortar and concrete were created by adding a polymer dispersion in latex or emulsion form to the plain cement-based mixture during the mixing process. The primary advantages of polymer latexes include their capacity to form flexible polymer films upon dehydration, as well as their ability to provide proper adhesion and cohesion in cementitious materials [12]. As previously mentioned, water-based polymer systems are utilized to enhance the properties of regular concrete, contributing to increased mechanical strength [10], improved workability [10,86], enhanced durability [13], reduced water absorption [88], and a decrease in overall porosity [89]. However, one limitation of these polymers is their potential for re-emulsification in humid alkaline conditions [10]. Due to their exceptional properties, cement-polymer composites are employed in various applications such as repair mortars, waterproofing membranes, self-leveling compounds, and tile adhesives.

Redispersible polymer powders (RDP) are a modern type of substances produced by spray-drying polymer dispersions and often used for the same purpose as polymer latexes. They are spray-dried to receive polymer powders [81]. It is important to emphasize that spray-drying auxiliaries strongly influence the properties of the RDP-modified mortar. It was observed that polyvinyl alcohol (PVA), which is an example of a colloidal stabilizer in the production of carboxylated styrene-butadiene latex, tends to screen the negative charges of polymeric carboxylate groups, which are to react with calcium ions. As a result, the process of forming a polymer film does not occur properly and the conversion from stage II to stage III is accelerated, as shown in Figure 3 and described in Section 3.1 [90,91].

The properties of cement–polymer concrete and mortars obtained using RDP powders are comparable to those formed in the process of polymer dispersion [93]. The major difference between these two types of concrete is the presence of the spray-dried auxiliaries in the first of the mentioned concrete types, which affects the composite properties. The spray-drying compounds adsorbed on the polymer surface need to dissolve or disperse from the polymer surface to allow coalescence and film formation. This requirement makes the polymer latexes less viable. Consequently, in many cases, they are replaced by an admixture of redispersible polymer powders because of their more straightforward application in concrete production.

3.1. The process of how the polymer film is formed within a cement-based matrix

The introduction of polymer into the cementitious matrix alters the microstructure of concrete [94]. The influence of adding polymer on the cement hydration process has been extensively studied in recent years. The nature of the relationship between polymer and cement particles is a topic of ongoing discussion among researchers. Many studies describe the physical interactions between the binders and the polymeric film created within the cementitious matrix, and their impact on the properties of hardened mortar and concrete. Scientists have also documented both chemical and physical interactions between cement and polymers, proposing the development of new complex structures and alterations in the morphology of cementitious materials, including changes in the composition and quality of hydrated phases [14]. The formation of a polymer film involves multiple stages, with researchers identifying four distinct phases (Figure 6).

The initial stage involves dispersing the polymer particles in water (solvent). As the water evaporates, the polymer particles agglomerate, leading to the formation of the second stage, which consists of a closely packed array with trapped water in the spaces between particles. The subsequent stage occurs as a result of water being expelled from these spaces through hydration and evaporation processes, resulting in a dense array of hexagonal, distorted polymer particles. Some researchers suggest an additional intermediate stage (Stage III*) between stages III and IV, characterized by a randomly packed array of distorted particles surrounded by water-filled spaces. Finally, stage IV is formed when the polymer particles coalesce into a uniform polymer film. The transition from stage III to IV only occurs if the ambient temperature exceeds the glass transition temperature (Tg) of the polymer [95,96].

3.2. Physical Characteristics of Cement-Polymer Composites

Redispersible polymer powders, when mixed with water, create a uniform dispersion with properties similar to the original polymer dispersed in water. The formation of the polymer film occurs as individual latex particles coalesce after dehydration. These substances are designed for one-time dispersion, so if hardened concrete becomes wet again, they remain unchanged. The resulting films exhibit increased cohesion in the fresh state and adhesion in the hardened state [97]. Polymers can enhance various fundamental characteristics of concrete, including mechanical properties, fresh mortar flowability, resistance to permeability and freezing-thawing, as well as corrosion resistance. Studies have shown that the addition of polymers to the cementitious matrix significantly alters its microstructure and the strength of physical and chemical interactions within the cementitious phase [15]. Numerous studies have been conducted on the attributes of polymer-modified cement materials. According to some reports, styrene-butadiene rubber (SBR) latex enhances flexural and tensile strength, carbonation resistance, waterproofing properties, and anti-shrinkage of mortar. Ethylene-vinyl acetate copolymer latex, widely used in concrete technology, yields result similar to SBR while also increasing flexural and tensile bond strength and concrete durability. Styrene-acrylic ester (SAE) copolymer latex enhances durability but reduces the elastic modulus of cementitious materials [6,12,15,89,92,98]. Similar findings were observed in studies on the effects of using redispersible powders in cementitious materials. Many researchers have confirmed that the application of RDPs improves the mechanical strength of mortar and concrete, such as compressive strength and flexural strength, which gradually increases depending on the RDP content used. Furthermore, it is generally agreed that admixtures of polymer powders affect several properties of concrete, including freeze-thaw resistance, water permeability, elasticity modulus, and corrosion resistance [18,98,99].

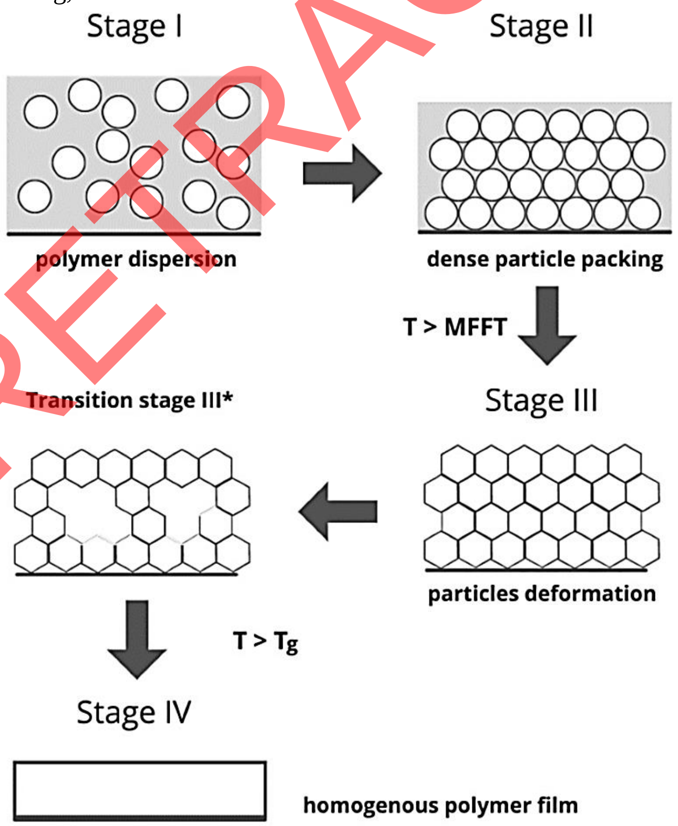

Figure 6. Diagram illustrating the formation of a polymer film from an aqueous dispersion, depicting stages I to IV (adapted from reference [95]).

Water permeability and curing conditions are critical factors that can impact the mechanical properties of concrete, ultimately affecting its service life. Young-Kug Jo [92] investigated the microstructure of polymer-modified concrete after curing in various conditions and the influence of these conditions on the tensile adhesion of concrete. The study examined three polymers—ethylene-vinyl acetate (EVA), styrene-butadiene rubber, and styrene-vinyl acrylic ester—in standard, dry, water, and high-temperature (70 °C) curing conditions. The adhesion in the tensile strength of polymer-modified concrete depends on both the type of polymer and the curing conditions. EVA achieved the highest adhesion in standard curing conditions, while dry curing provided adequate drying time for polymer film formation. However, in humid conditions, the polymer film was not uniformly dispersed in the cementitious matrix, resulting in lower adhesion after water curing [92]. In a separate study, S. Gwon et al. [18] investigated the impact of adding an acrylic redispersible polymer powder on the microstructure development and mechanical properties of ultra-rapid hardening concrete. The study focused on compressive strengths, rheology, hydration phase evolution, porosity, morphological transition, and setting time. Results indicated that adding a polymer delayed setting time but significantly strengthened the microstructure of ultra-rapid hardening cement systems. The optimal polymer-to-cement ratio was determined to be approximately 10% based on test results [18]. Medeiros et al. [14] confirmed that applying EVA or acrylate polymers to cement blends increased compressive tension and direct-shear bond strengths. Silva and Monteiro [100] examined the influence of EVA powder and cellulose ethers on the hydration of Portland cement phases, particularly C3S and C3A. Microscopic imagery revealed that EVA copolymer particles tended to agglomerate around C3S grains during hydration and acted as nucleation sites for the CSH phase. However, introducing EVA into the cementitious matrix hindered ettringite formation in the initial hours of cement hydration [100]. Studies involving vinyl acetate and versatate copolymer (VA/VeoVa) demonstrated improved resistance to alkaline hydrolysis compared to other copolymers containing vinyl acetate groups [101]. Additionally, VA/VeoVa powder exhibited water-reduction effects and retained water in cement mortar, significantly improving concrete toughness and reducing shrinkage rates. Furthermore, VA/VeoVa powder facilitated air entrapment, increasing total air content in fresh mortar. However, Wang et al.'s work showed that VA/VeoVa polymer powder reduced the compressive strength of concrete [15].

3.3. Effects of Aging on Cementitious Blends Modified with RDP

The presence of water leads to a partial prehydration of the cement surface and the polymer film formation. Polyvinyl alcohol (PVA) present on the redispersible polymer powder (RDP) particles' surface, which acts as a colloidal stabilizer in the spray-drying process, might dissolve in humid conditions, allowing the polymer powder to coalesce into a film, partially protecting the cement particles from aging. As a result, the mechanical properties, such as compressive and flexural concrete strengths, with RDP powder achieve higher values than concrete without RDPs after conditioning in humid air [19].

There is little information in the literature pertaining to the long-term performance and durability of cement–polymer concrete, especially with redispersible powder polymers. J. Schulze and O. Killermann [102] examined and described a long-term performance of three different RDPs admixtures, i.e., vinyl acetate-ethylene, styrene-acrylic and ethylene-vinyl chloride-vinyl laurate. They have established that the morphology of the polymers in the cementitious matrix does not change over the 10-year long storage, neither in dry nor humid conditions. The polymer particles were distributed in the matrix and formed secondary reinforcement in the pores and flaws of cementitious blends. Cement serves as an inorganic binder that contributes to compressive strength, while the redispersible powder, an organic binder, affects internal tensile strength and adhesion bond strength at interfaces. Both cement and redispersible powder work together to enhance the properties of mortar and concrete [19,102].

4. Fiber

The literature review uncovered numerous studies on the use of fibers in cement-based composites, known as fiber-reinforced concrete. Adding fibers to a cement blend enhances the mechanical properties, toughness, ductility, and resistance to cracking in mortar and concrete. Over the past few decades, various types of fibers have been investigated for use in cement-based materials. Steel fibers, glass fibers, natural fibers, and polymer fibers are the primary types used for concrete reinforcement. Steel fibers have been traditionally favored due to their ability to significantly improve the tensile and flexural strength of cementitious materials by absorbing energy and controlling cracks. Additionally, their high electrical and heat conductivity makes them suitable for special conditions. However, corrosion is a major drawback that can compromise the durability of structures made with steel fiber-reinforced concrete. Glass fibers and natural fibers such as wood, coconut, palm, and vegetable fibers also provide good reinforcement but come with significant limitations. Glass fibers have poor alkali resistance, while natural fibers lack durability. The use of randomly distributed polymer-based fibers in the cement matrix has garnered considerable attention due to their effectiveness in enhancing the fundamental characteristics of concrete (Figure 7).

The application of polymer fibers has resulted in advantageous outcomes such as resistance to corrosion and alkaline reactions, salts, chlorine, and microorganisms. R.F. Zollo [103] has presented a schematic crack arrest mechanism for fiber-reinforced concrete (Figure 8). The diagram illustrates the ability of the fibers to absorb energy and control crack propagation. It depicts fiber rupture (1) and pull-out (2), tension bridging through the fiber (3), and debonding of the fiber from the matrix, effectively dissipating energy to prevent crack growth. The presence of fibers in the matrix (5) helps confine the cracking area, resulting in smaller cracks distributed in the adjacent space of the cementitious matrix, as shown in Figure 8. The reinforcing effect observed in concrete is not solely due to individual fibers but rather a cumulative effect of all fibers. In traditional concrete, micro-cracks are present even before loading due to drying shrinkage causing volume contraction. Some researchers have reported a decrease in drying and plastic shrinkage cracks due to fiber use [25,104]. Generally, micro-plastic fibers with lengths ranging from 5–30 mm and diameters from 5 to 100 μm can effectively reduce plastic shrinkage cracking. The prevention of crack propagation in concrete by micro and macro-fibers is depicted in Figure 9. Macro-plastic fibers ranging from 30 to 60 mm in length are utilized to control shrinkage, particularly drying shrinkage. The formation of plastic shrinkage cracks can be attributed to moisture loss after casting. If the rate of moisture evaporation exceeds 0.5 kg/m2 per hour, it can lead to internal strain induced by increasing negative capillary pressure within the matrix. Plastic shrinkage occurs at an early stage when the concrete strength has not yet developed [105]. Kim et al. [25] examined the impact of fiber geometry and volume fraction on moisture loss rate and plastic shrinkage cracking. They found that the volume of macro-plastic fibers and their geometry do not affect total moisture loss, while plastic shrinkage was reduced when the fiber fraction reached 0.25%.

According to the literature, the synthetic fibers most frequently utilized in concrete are polypropylene (PP) fibers, polyamide (PA) fibers, polyethylene (PE) fibers, and polyvinyl alcohol (PVA) fibers. All of these fibers are distinguished by their low density, resulting in a high volume of fiber content in the cementitious matrix relative to the mass of the fibers.

In recent years, researchers have examined how synthetic fibers affect the rheology and mechanical characteristics of cement-based materials. They have explored the impact of different types of fibers, which vary in chemical composition, volume within the cementitious matrix, size (macro- and micro-), and geometry [25,108]. Additionally, they have investigated the influence of individual and combined (various lengths and sizes) polymer fibers on concrete [27,110].

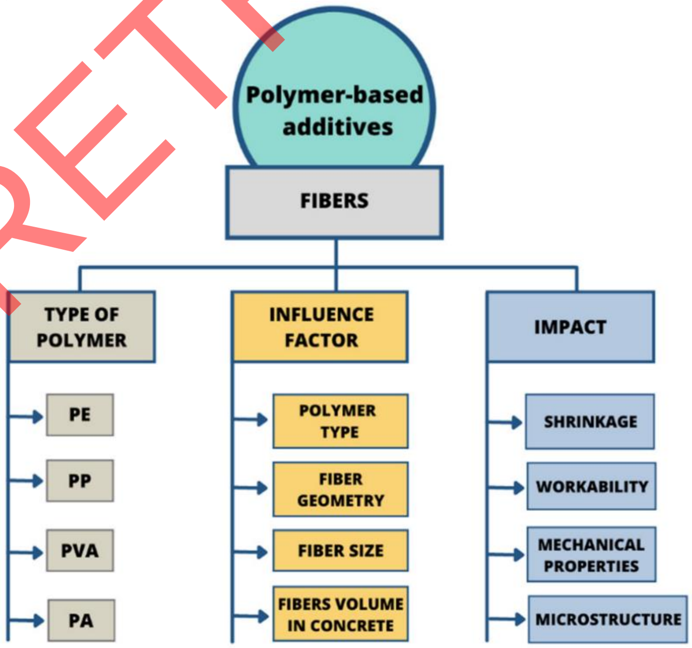

Figure 7. Impact of polymer fibers on the characteristics of concrete-based composites.

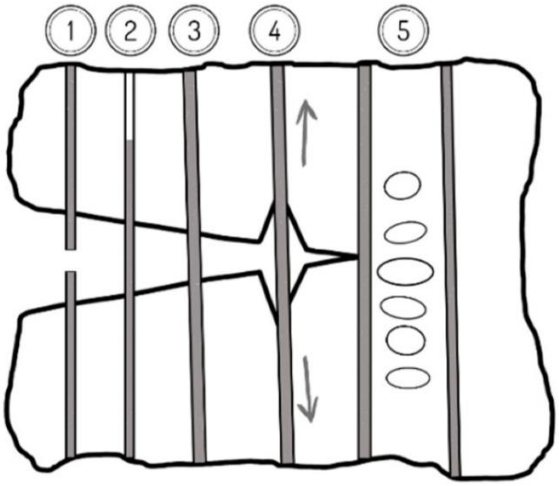

Figure 8. The diagram illustrating the absorption of energy between concrete and fibers (based on literature [103]). (1) Failure of the fiber; (2) pulling out of the fiber; (3) bridging by the fiber; (4) separation of the concrete matrix from the fiber; (5) cracking of the concrete matrix.

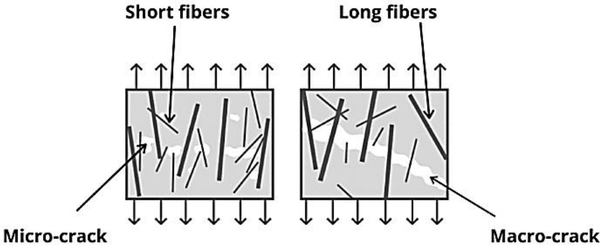

Figure 9. Prevention of crack spread in concrete reinforced with fibers [107].

4.1. The Rheological Characteristics and Mechanical Attributes of Cementitious Materials with Fibers

The inclusion of fibers in the cementitious matrix affects both the fresh and hardened states of concrete. It is widely recognized that polymer fibers decrease the workability of fresh mortar [106]. This occurs because a network structure forms within the concrete matrix, impeding the flow of the mixture. Additionally, a high volume and surface area of fibers can cause water adsorption, thereby increasing mortar viscosity [105,111]. However, Ramezanianpour et al. [28] proposed that the reduced workability of mortar with a higher fiber content in the cementitious matrix is due to trapped air in the inner pores. M. Tabatabaeian et al. [106] examined the rheological properties of fresh concrete reinforced by fibers and found that steel fibers cause a slight decrease in slump flow, while polypropylene fibers significantly reduce it. Yap et al. [112] demonstrated that mortar workability depends on micro-fiber geometry, with fibrillated polypropylene fibers having a lower effective surface area, resulting in better workability compared to multifilament fibers [113]. Hydrophobic polyolefin fibers such as polypropylene and polyethylene were observed to have similar effects on concrete properties, including fresh blend rheology. PE fibers were found to decrease slump flow to a similar extent as PP fibers [112,114,115]. The presence of PVA fibers leads to a reduction in workability proportional to an increase in fiber content. PVA fibers have a more significant effect on flow reduction than PE and PP fibers due to their hydrophilic nature [114]. As previously mentioned, the impact of fibers on concrete's mechanical strength depends on their size, chemical structure, and quantity within the cementitious matrix. Research by Yin et al. [105] suggests that macro-plastic fibers in cementitious materials have no significant impact on compressive strength, consistent with findings reported by Behfarnia and Beharvian [116]. However, Felekoğlu et al.'s study [117] showed that adding PP macro-fibers increased the compressive strength of foamed concrete.

Additionally, Gencel et al. [118] have verified the enhancement of compressive strength in self-compacting concrete resulting from the inclusion of PP macro-fibers. Ramezanianpour et al. [28] studied the impact of PP fibers on the mechanical properties of concrete for sleeper use and found that increasing the amount of PP fibers gradually decreased the compressive strength of concrete sleepers. M.Tabatabaeian et al. [106] examined the influence of PP fibers on the mechanical properties and durability of high-strength SCC compared to steel fibers, revealing a decrease in compressive strength with the incorporation of PP fibers. Furthermore, replacing steel fibers with PP fibers in hybrid mixes resulted in reduced compressive strength across all hybrid samples. Hybrid fibers have garnered attention due to their superior effects on composite performance compared to single fiber blends, as demonstrated by Chen and Liu's study [110] on high-strength lightweight concrete. Hsie et al. [119] investigated polypropylene hybrid fiber-reinforced concrete, finding that adding mixed PP macro- and micro-fibers to the cementitious matrix increased compressive and flexural strength compared to single fibers. Yun's research focused on PVA/ultra-high molecular weight PE hybrid fiber-reinforced concrete, showing that a higher amount of PVA fibers improved compressive performance compared to samples with more PE fibers [119]. Guler [108] explored the use of PA fibers in hybrid form in cement-based composites, finding that while the addition of both PA macro- and micro-fibers did not notably increase compressive strength, it did significantly enhance flexural strength. Cao et al. [109] developed a new multiscale hybrid fiber system comprising CaCO3 whiskers, PVA, and steel fibers, which significantly improved the mechanical properties of cementitious materials, enhancing flexural strength, energy absorption capacity, and reducing plastic shrinkage in concrete based on previous tests.

4.2. The Microstructural Composition of Cement-Based Materials Reinforced with Synthetic Fibers

The analysis of microstructure is a suitable approach for understanding the physical and mechanical properties of fiber-reinforced cementitious materials, and as a result, researchers have placed significant emphasis on the microstructural characterization of concrete. The literature review has identified numerous articles focused on studying the microstructures present in fiber-reinforced concrete using various techniques, including scanning electron microscopy (SEM) [28,120,121,122], energy dispersive spectroscopy (EDS) [123], X-ray diffraction analysis (XRD) [26,120,121,124,125], infrared absorption spectroscopy (IR) [123], Fourier transform infrared spectroscopy (FTIR) [120,123], and thermogravimetry analyses (TGA) [124]. Generally, the hydrophobic nature of polymer plastic fibers results in poor bonding in hydrophilic cementitious materials. SEM analysis reveals the presence of trapped air voids around polyolefin fibers (Figure 10). To address this issue, some researchers have modified the surface of fibers using chemical solutions [126,127,128] and plasma treatment [129]. Lopez-Buendia et al. [128] discussed the surface modification of polypropylene fibers through alkaline treatment (Figure 11), which led to cement crystal growth on the modified fibers' surface and improved fiber-cement adhesion. The literature review indicates that surface treatment enhances the mechanical properties of hardened concrete, such as flexural strength [127,129], crack strength [126], and toughness [126,129].

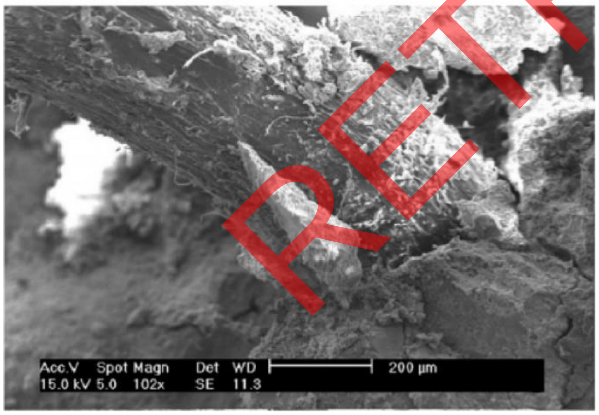

Figure 10. Inadequate adhesion and air voids trapped around a PE fiber within the concrete matrix [131].

Another method of surface modification for fibers that has been experimentally tested is thin layer coating. Hernandez-Cruz et al. [129] examined the chemical interactions between PP fibers coated with ethylene acrylic acid copolymer (EAA) and the cementitious matrix. They discovered that in the cement paste containing the EAA-coated fibers, bonding is enhanced due to the hydrophilic carboxyl groups present in EAA, which interact with the Ca2+ and Na+ cations from the cement paste. This improved bonding enhances the post-cracking behavior of concrete reinforced with the modified fiber compared to concrete reinforced with non-modified PP fiber. C. Signorini et al. [130] studied the impact of silica-coated PP fibers on the mechanical properties of fiber-reinforced concrete. Polypropylene fibers were coated with silica nanoparticles using the sol-gel technique. They found that nano-silica coating is an effective method for improving bond strength in the fiber-cementitious matrix. The SEM analysis (Figure 12) reveals that the surface of the fiber in a control sample appears scratched, with mortar adhering to its surface only in some places, whereas on the surface of modified fibers, attached mortar grains are visible.

4.3. Characteristics of Concrete Reinforced with Recycled Polymer Fibers

Recently, the potential use of recycled plastic waste fibers in concrete has garnered attention from researchers. A number of experimental studies have been conducted to investigate reinforcing concrete with recycled plastic fibers [131,132,133,134,135]. The focus has primarily been on plastics found in waste in significant quantities, such as PET fibers, rubber aggregates, and polystyrene wastes. These plastics are being tested as a partial replacement for sand in concrete, with an exchange ratio of 10% by volume potentially saving 820 million tons of sand per year [134].

B.S. Al-Tulaian et al. [133] examined the effects of recycled PET waste fibers on the mechanical properties of Portland cement mortar, including flexural strength, flexural toughness, and shrinkage cracking. They found that adding fibers reinforced concrete and led to increased flexural toughness and strength. Moreover, increasing the fiber volume fraction significantly improved the reduction of plastic shrinkage cracking. Different types of tested fibers varied in length and volume fractions but all resulted in a decrease in total crack areas and widths.

Ochi et al. [134] studied the bond behavior of concrete reinforced with recycled PET fibers from waste bottles. Samples with fiber content above 1% exhibited higher bending strength than reference samples. A similar effect was observed by Kim et al. [25], who studied the performance of concrete with different types of shredded, recycled PET. Embossed fibers showed superior mechanical bond strength followed by crimped and straight fibers. Additionally, samples with the highest bond strength also demonstrated the best resistance to plastic shrinkage cracking.

The influence of recycled PET fibers on early-age performance and mechanical characteristics of reinforced concrete has also been investigated. Borg et al. [31] used fibers shredded from waste plastic bottles of different sizes

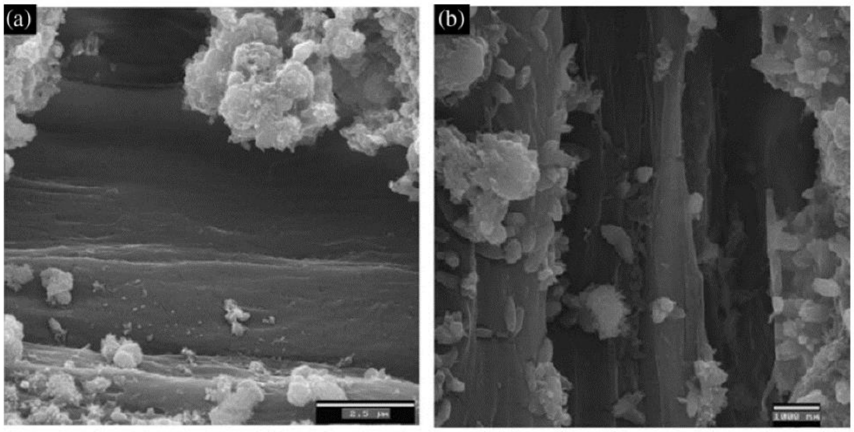

Figure 11. The exterior of polypropylene fibers: prior to alkaline treatment (a) and following alkaline treatment (b) [128].

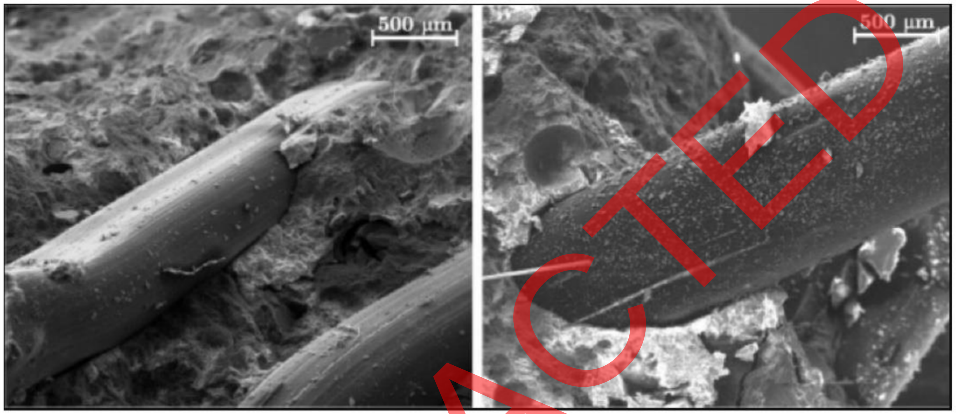

Figure 12. The appearance of the samples after the bending test: unmodified PP fibers (on the left) and PP fibers coated with silica (on the right) [130].

and geometries and found that their addition reduced compressive strength but restrained crack development induced by an environmental chamber.

M. Horgnies et al. [136] studied the effect of PA wastes on the microstructure of lightweight mortars and found that compressive strength decreased proportionately with an increase in polymer waste content while total porosity increased.

These studies demonstrate the potential benefits and challenges associated with using recycled plastic waste fibers in concrete applications [131,132,133,134,135].

5. Conclusions

In summary, research has been conducted on enhancing concrete by incorporating polymer-based additives into the cement matrix. The effects of adding superplasticizers, latexes, redispersible powders, admixtures, fibers, and recycled polymers to concrete have been explored. Reviewing the literature has led to several conclusions. The addition of a plasticizer or superplasticizer can achieve the desired consistency by reducing water or cement content. Key factors influencing the properties of resulting concrete composites include the type, number, and density of adsorbing groups, side-chain length, and grafting density. Additionally, the dosage and quantity of superplasticizer used significantly impact its efficiency in adhering to cement particles. Redispersible powders and polymer dispersions influence the cement hydration process and can form flexible polymer films after dehydration, providing proper adhesion and cohesion in cementitious materials. Polymeric fibers are known for their elasticity, chemical resistance, high strength, and excellent wear resistance. Consequently, cement-based materials containing fibers exhibit improved mechanical properties, toughness, ductility, and post-cracking resistance. Furthermore, the low melting temperature of polymeric fibers results in reduced spalling in concrete composites at higher temperatures. The literature review demonstrates that polymer-based additives are valuable components that can overcome limitations in concrete. Future studies are likely to focus on self-repairing concrete composites. Technological advances have been made to produce concrete without reinforcement using self-compacting technology with high aesthetic values and quality while being lighter, safer, more flexible, durable, and environmentally friendly. Additionally, future concrete may have the potential to utilize solar and wind energy and capture/consume CO2 and NOx.

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