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A Review on the Use of Polypropylene Fiber in Concrete and Bibliometric Analysis

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ABSTRACT

The use of polypropylene fibres (PF) has aroused great interest in science and the construction industry. This is mainly due to the numerous benefits they offer in terms of sustainability relative to steel fibres and steel fabrics. This study provides a comprehensive assessment of the current state of knowledge and technological advances in the use of PF to enhance the strength of concrete. A comprehensive analysis of the impacts of PF on the fresh and mechanical properties of concrete is presented. The effects of PF on various aspects of durability such as water absorption, chloride penetration, sulphate resistance, drying shrinkage, carbonation resistance and fire resistance are also reviewed. The workability of concrete is impacted by the addition of PF. The formation and progression of initial microcracks is reduced in concrete containing PF. Use of PF significantly improves the tensile and flexural strength of concrete. Concrete produced using PF demonstrate better sulphate, chloride and fire resistance properties. Further research on its use as sole fibre or blended with other types of fibre in modern concretes and blended cement concrete remains to be discovered.

1. Introduction

Concrete is considered the most widely used building material due to its affordability, broad spectrum, exceptional load-bearing capacity, and wide range of applications in construction [1]. However, the main problems of conventional concrete include its low tensile strength, limited crack resistance and low ductility, which limit its use in construction [2-4]. The main limitation of concrete is that it is not able to resist cracking throughout its life, which is often the case in the early stages of a building's life. The formation development action of cracks can affect the mechanical properties and durability of a structure, including impermeability, frost resistance, strength, and toughness

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which can affect service life and safety. To solve this problem, the researcher has incorporated fibres into the concrete to prevent or regulate the formation, propagation, or coalescence of cracks [5]. The ability of fibers to bridge a fracture and transfer stresses leads to an improvement in structural response, which can be associated with improved crack width control. In addition, extensive studies have shown that the incorporation of fibres can significantly improve many structural properties of concrete, such as compressive strength, static flexural strength, shear strength and tensile strength [6-8]. Hence, a new form of concrete composite has been developed in the recent decades, known as fibre-reinforced concrete (FRC). FRC is a type of composite material consisting of a cement-based matrix and fibers that are evenly and randomly distributed throughout the material to provide discontinuous reinforcement [9].

The most used fibres in concrete include low modulus fibres such as nylon [10], polyethylene [11] and polypropylene [12,13], and high modulus fibres such as steel [13,14], carbon [15], and glass [12,16]. Among these fibres, polypropylene fibres are increasingly attracting research interest as synthetic fibres due to their cost efficiency, light weight, corrosion and acid resistance, high toughness, and improved resistance to shrinkage cracking [17]. On the other hand, the polypropylene fibres significantly improved the resilience, toughness and fracture control of FRC composites, although they have a low modulus of elasticity [18]. Therefore, the use of PF in concrete is becoming increasingly popular in practice. In addition, there are reports indicating that the inclusion of polypropylene fibers has minimal impact on air content and fresh density due to the low density of PF compared to other fiber types such as steel fibers. PF-reinforced concrete, on the other hand, takes less time to mix than steel fiber-reinforced concrete [19]. Polypropylene fibres (PP fibres) are often used in concrete structures to improve their properties and durability due to advances in concrete technology [20].

Scientists have thoroughly researched the mechanical properties and durability of polypropylene fibre reinforced concrete (PFRC) using a variety of testing methods. Currently, there is no summary of the status of these studies. The review helps us to understand how PF affects different types of concrete and to familiarise ourselves with different research methods that can serve as a basis for future PFRC research. In this study, the recent literature is thoroughly reviewed and the current state of research on the basic mechanical properties and durability of PFRC under different test conditions is presented. The aim is to summarise the latest research on PFRC and suggest ways to optimise the performance of PFRC to better suit complex application scenarios and maximise its effectiveness. The first part (introduction) of this study sets out the research criteria for the investigation. Section 2 describes the methodology of the bibliometric study and presents the annual publication pattern and the coincidence of keywords. Section 3 discusses the properties of polypropylene fibres. Section 4 discusses the effects of polypropylene fibres on the strength properties of concrete. The next part of this study examines how polypropylene fibres affect the durability properties of concrete. Section 6 contains concluding considerations and recommendations.

2. Methodology

First, a rudimentary bibliometric analysis was performed to objectively evaluate the general state of the use of polypropylene fibres in the field of concrete research. Bibliometric analysis is a common method to visualize the corpus of scientific publications and assess the current state of research in each discipline [21]. Data from the Scopus database was used for the study. Scopus is the most widely used indexed database in this field of research [22,23]. Only academic publications and reviews published in the category of polypropylene fibres in concrete were considered in this study. Non-academic materials such as editorial materials, correspondence, reprints, and other document types were excluded from the search. A selection of materials, including articles and reviews, published in the period from 2003 to 2023 was made. A comprehensive analysis was conducted for a total of 2,047 publications and reviews within the specified time, considering the required restrictions, which ended in November 2023.

In order to capture the structure of knowledge and prevent subjective distortions, a literature search was carried out based on a content analysis in which the terms in the texts of the publications were linked to each other based on their collocations. The concise representation of a core phenomenon through content analysis is the overarching goal [24]. A common content analysis technique is word frequency analysis, which is intended to draw attention to the central aspects of the topic under investigation. In this way, growth trends and changes in the scientific discourse on a particular topic can be identified [25]. To specifically identify current topics in the field of polypropylene fibres, synonymous terms and phrases are first summarized and then grouped together. The structure of the Use of polypropylene fibre in concrete study was displayed using the VOS Viewer Tool. By classifying the underlying study according to the textual content (terms, keywords), the scientific maps were developed to categorize the current state of knowledge. The scientific maps were created using co-occurrence as a keyword. The VOS viewer tool used association strengths determined by the number of co-occurrences of a keyword.

2.1 Yearly Publication Trend

A snapshot of the state of research on a particular topic can be obtained by quantifying and analysing the number of publications within a given period. This can also provide insight into the likely future development of the field [24]. Figure 1 shows the annual publication trend for the searched keywords. In 2010, only 147 articles were published. Following then, the overall number of articles grew gradually but steadily, culminating in 628 publications in 2017. Nonetheless, there was a notable surge in publications, reaching 2047, between 2017 and 2023. Based on these findings, the use of polypropylene fibre in concrete appears to have gone through three distinct phases: an initial build-up phase (2003-2010), a phase of gradual acceleration (2010-2017), and a projected rapid expansion.

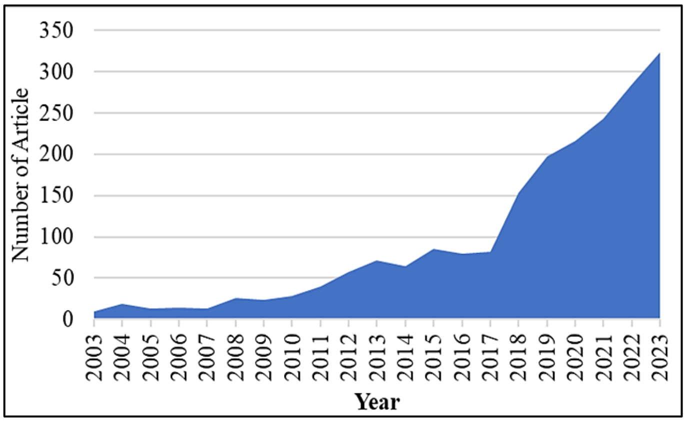

Fig. 1. Annual publication trend from 2003 to the end of December 2023 for the use of PF in concrete

2.2 Keywords Co-Occurrence

Keywords are an important research tool because they identify and highlight important areas of research. The VOS Viewer analysis revealed that the top five keywords were “Polypropylene”,

“Polypropylene fiber”, “Fibers”, “Reinforced concrete”, and “compressive strength”. Figure 2 shows a global map of associations for the keyword. Only terms that repeat more than 60 times are counted. 68 terms meet this criterion. The various colour denotes distinct groups(cluster) of related keywords. A frame represents the prevalence of keywords and the links between them in the literature; the more often mentioned keywords will have a larger frame, and the more significant links among them will be represented by a thicker line. Four clusters were found, shadowed by red, green, blue, and yellow colour. It was found 19 keywords in cluster 1 (red), 18 keywords in cluster 2 (green), 17 keywords in cluster 3 (blue) and 14 keywords in cluster 4 (yellow). The first cluster includes terms such as " Polypropylene”, “reinforced concrete" and "steel fibres", suggesting that the use of polypropylene fibres to reinforce concrete.

In addition, the second (green) cluster refers to the effect of polypropylene fibres on the mechanical properties of concrete. The second cluster includes terms such as “Tensile strength”, “Mechanical properties”, “Flexural strength”. The third cluster, in blue colour (cluster #3), is mostly focused on the durability of the concrete with polypropylene fibre. The third cluster including terms such as “Compressive strength”, “Durability”, “shrinkage” and “water absorption”. The fourth cluster in yellow (cluster 4) is mainly concerned with the effect of polypropylene fibres on the fire resistance of concrete. The fourth cluster including terms such as “Polypropylene fibre”, “Concrete”, “Spalling” and “Elevated temperature”.

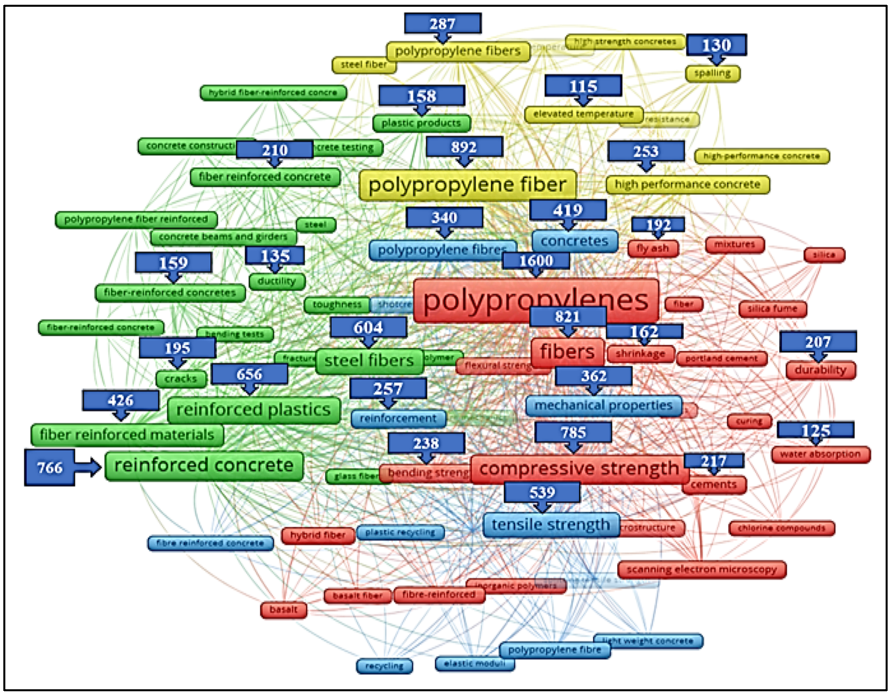

Fig. 2. Network visualization of the co-occurrence of terms used by researchers in the literature on the use of PF in concrete

3. Properties of Polypropylene Fibers

This Polypropylene Fibres (PF) appears like a white short strip as illustrated in Figure 3. PF varies in both length and diameter. PF can be divided into macro and micro forms based on their length and cross-sectional characteristics. Macro fibres are between 30 and 60 mm long and have a cross-sectional area of 0.3 to 1 mm^2. In contrast, microfibers typically have dimensions of 6 to 20 mm in length and 5 to 300 µm in diameter [26]. The physical and mechanical properties of PF used as reinforcement have a significant influence on the properties of concrete.

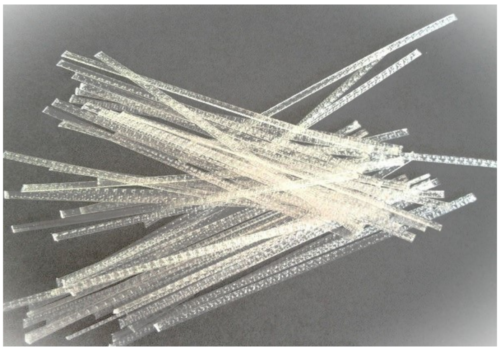

Fig. 3. Polypropylene fibres

Table 1 provides comprehensive information on PF, which is frequently cited in the scientific literature. Key parameters such as length, diameter, density, tensile strength, modulus of elasticity, and elongation at break are frequently cited as fundamental data in the literature. It is crucial to recognize the considerable differences in the properties of polypropylene fibres, especially in terms of modulus of elasticity. This property is of great importance for the use of fibres in the production of cementitious composites. The physical characteristics of PF differ widely based on the method of production [27]. From the available data, it can be deduced that the tensile strength and modulus of elasticity of micro-PF have values of around 270 to 1000 MPa and 0.3 to 8 GPa respectively. The tensile strength of macro-PF ranges from 400 to 1345 MPa, while the modulus of elasticity is between 4.7 and 10 GPa.

Table 1
The physical properties of PF

References	Length (mm)	Diameter (mm)	Aspect ratio	Specific gravity	Tensile strength (MPa)	Elastic modulus (GPa)	Breaking elongation %
Yuan and Yanmin [12]	12	0.06	200	0.91	486	4.8	
Ahmad *et al.,* [28]	35	.55	64	-	1345	-	
Akid *et al.,* [1]	12	.24		0.91	550		
Guo *et al.,* [29]	19		200	0.91	400	3.79	
Liu *et al.,* [30]	12	.15		0.91	276		
Ahmed *et al.,* [31]	12			0.91	600-700	3-3.5	
Wang *et al.,* [32]	12		600		650	3.5	
Shen *et al.,* [33]	12	.15		900 kg/m^3	800-1000	8.0	
Bhogone and Kolluru [34]	60	0.60			550-640	7-10	
Tran *et al.,* [35]	6	0.030		0.91	600	2.8	
Fu *et al.,* [36]	19	0.030		0.91	270	0.3	
Ibrahim *et al.,* [37]	12	0.032		900 kg/m^3	650		
Liang *et al.,* [38]	50	0.8		0.95	706	7.4	
Guo *et al.,* [39]	19		200		400	3.79 GPa	
Liang *et al.,* [40]	19	0.0261		0.91	641	10.6	26.0
Yang *et al.,* [41]	19	0.0261		0.91	641	4.5	40
Cui *et al.,* [42]		0.048	167, 280, 396	0.91	400-450	5 GPa	
Hossain *et al.,* [5]	12			0.91	480	7.0	
Qin *et al.,* [43]	19	0.0312		0.91	562	5.9	27
Kheyroddin *et al.,* [44]	18				400	2.7	80
Hussain *et al.,* [45]	12	0.03	400	900 kg/m^3	500	5	

Liu *et al.,* [46]	20	0.08		910	680	3.75	17
Bentegri *et al.,* [47]	19	0.34		0.92	689	5.75	
Ye *et al.,* [48]	18	0.032	562.5	-	410	-	15
Deng *et al.,* [49]	50	.8	63	.95	706	7.4	10
Eidan *et al.,* [50]	12	0.078	154	0.91	300-400		
Alwesabi *et al.,* [51]	3		80	0.91	550		
Mo *et al.,* [52]				0.91	490	3.5	15
Atea [53]	12	0.018	667	0.91	300-400	3.5-3.9	
Zhou *et al.,* [54]	12	0.048		0.91	450	3.5	
Akhmetov *et al.,* [55]	6-15	0.018-0.021		0.91	320-600	3.5-3.9	
Li *et al.,* [56]	19				276	3.8	
Ali *et al.,* [57]	12	0.02		900 kg/m^3	400		15%
Zeyad *et al.,* [58]	12	0.018		910 kg/m^3	350		
Dong *et al.,* [59]	-	-	-	0.8	265	3.782	14
Tayeh *et al.,* [60]	-	-	-	940	275	2.95	3.5
Wang *et al.,* [61]	14	0.035	400	0.91	293	3.4	35
Alrshoudi *et al.,* [62]	30	0.45		910	400		
Altalabani *et al.,* [63]	12	0.032		0.91	272	3.5	
Mohammadhosseini *et al.,* [64]	30	0.45		910	400		
Lee *et al.,* [65]	58	0.63		0.91	650	6.0	15
Wang *et al.,* [66]	38			0.91	570-660	4.7	
Akın *et al.,* [67]	54	0.65		0.91	550-750		

4. Fresh Concrete Properties
4.1 Workability

Figure 4 illustrates the effect of PF content on workability of concrete. In general, the workability of the mixtures was significantly reduced by the addition of PF, as the internal friction was increased by the higher PF concentration, while the water-binder ratio remained constant [36,68-77]. The slump value of concrete decreased when the length and dose of fibres increased [17]. This indicates that incorporating PF negatively affects the workability of the concrete. The observed phenomenon could be due to the innate tendency of the fibres to intertwine, which leads to problems with uniform distribution in the concrete matrix [57,78]. In addition, the reduction in slump is attributed to the inclusion of polypropylene fibres in the concrete, which leads to a stronger interlocking of the particles in the first mixing phase [68,79].

Moreover, Due to its high content and large surface area, PF has a considerable ability to effectively absorb cement paste, encapsulate it and increase the consistency of the concrete mix [80]. These effects collectively result in decreased workability [80]. The workability and uniformity of a freshly mixed concrete mix with PF are significantly influenced not only by the concentration of the fibres but also by the length and geometric characteristics of the fibres [55]. However, several studies have indicated that the negative effects of PF on the workability of concrete can be reduced by incorporating fly ash as substitutes for cement [1,81,82]. The reason for this occurrence can be attributed to the spherical shape of fly ash particles, which in turn reduces any possible rise in concrete's water demand [83].

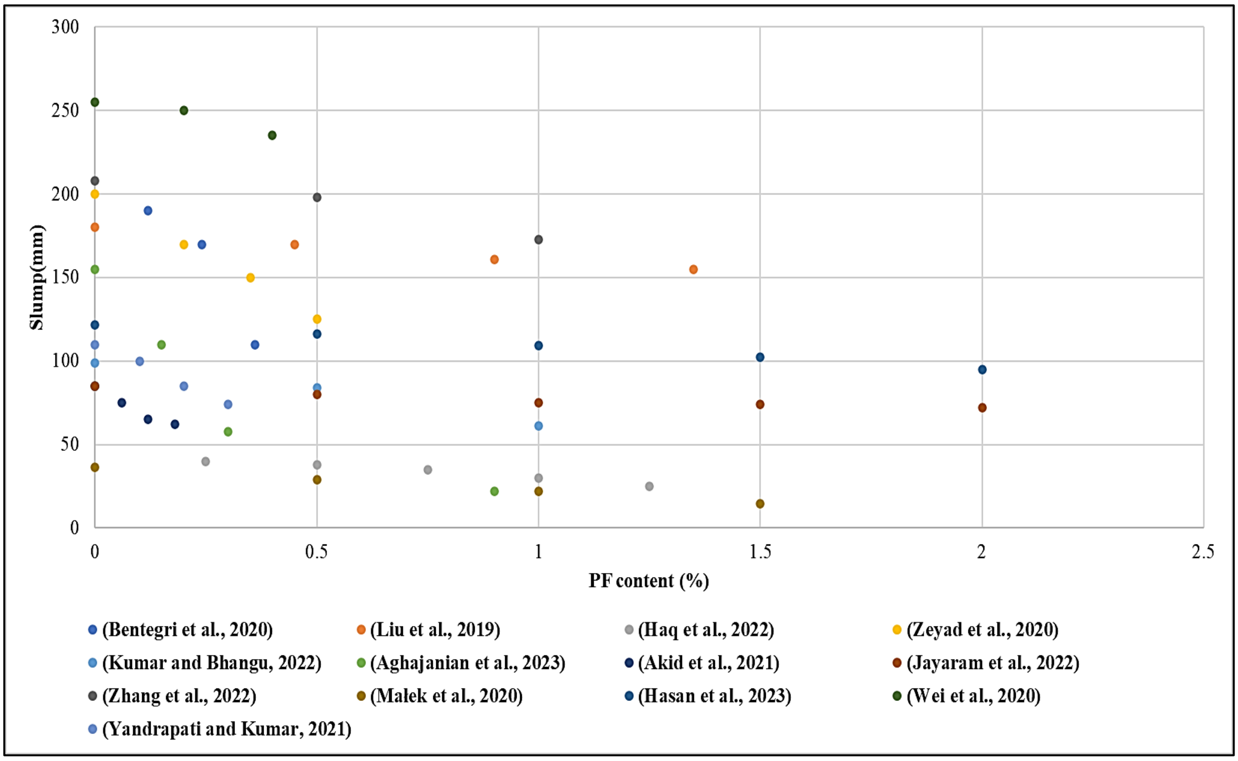

Fig. 4. Influence of the PF content on the workability of concrete [58,84-95]

5. Hardened Concrete Properties

5.1 Compressive Strength

Figure 5 illustrates the relationship between the proportion of PF and the corresponding change in 28-day compressive strength of the concrete. Several studies have shown that the use of PF up to a certain limit led to a significant increase in compressive strength compared to conventional concrete [31,48,58,70,73,88,89,92,93,96-98]. It is worth noting that the compressive strength of concrete does not increase significantly at lower fibre contents. The use of up to 0.1 % PF led to a limited increase in compressive strength, which reached a maximum of 5 % compared to conventional concrete [48,70,93,99]. On the other hand, several research studies have shown that the addition of PF between 0.1 and 0.6 % leads to an increase in 28-day compressive strength of up to 20 % compared to conventional concrete [31,48,89,97]. Alternative studies have shown that a PF content of up to 1 % can significantly increase the 28-day compressive strength of concrete compared to conventional concrete [70]. The increase in compressive strength observed with PF could be due to the improvement in micro-cracking in the concrete. This is because the fibres act as a linking medium, which leads to increased compactness of such composite [69,100,101].

In addition, this could be attributed to fact that PF are characterised by a high degree of flexibility. During the mixing and casting process, the PF tend to curl, which facilitates the filling of voids and thus leads to their reduction [51]. However, the excessive use of PF fibres can lead to a reduction in compressive strength after 28 days. The main cause of this phenomenon is the presence of an excessive number of fibres, which leads to an uneven distribution of fibres in the concrete. This uneven distribution of fibres consequently contributes to an increase in the number of internal defects in the concrete [36]. In addition, the presence of an excessive number of fibres can lead to the introduction of a significant number of air bubbles during the mixing process, resulting in a reduction in the compressive strength of the concrete [1].

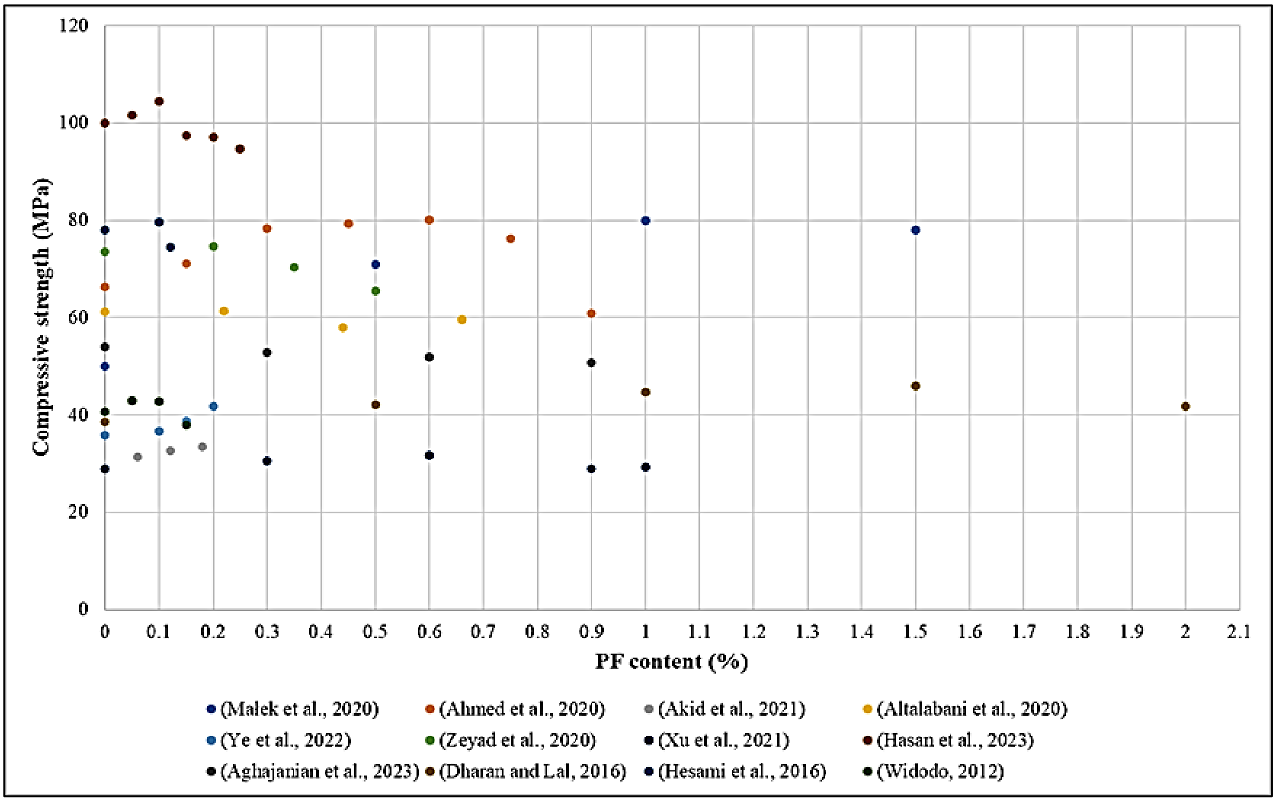

Fig. 5. Influence of PF content on concrete compressive strength [31,48,58,70,73,88,89,92,93,96-98]

5.2 Splitting Tensile Strength

The Figure 6 shows the relationship between the proportion of PF and the resulting change in the 28-day splitting tensile strength of the concrete. The increase in splitting tensile strength due to the presence of PF can be seen in the figure. Previous studies [12,31,57,58,89,92,94,97,102-106] have shown that the use of PF within a certain limit led to a remarkable increase in splitting tensile strength compared to conventional concrete. As illustrated in Figure 6, the splitting tensile strength exhibits a notably high value within the PF content range of 0.6% to .9%. The splitting tensile strength of the concrete increased by a factor of 0.25 to 1.7 when the volume addition of PF was kept below 0.9 %. The increase in tensile strength can be explained by the bridging phenomenon exhibited by fibres, which effectively limits the spread of microcracks during the initial stages of concrete formation [37]. In addition, the splitting tensile strength of the concrete mix increases with increasing fibre quantity due to the favourable tensile strength of the fibres. Responsible for this phenomenon is the formation of a strong bond between aggregate and cement paste, which is caused by the large number of fibres along the fracture plane before fracture [5].

According to Shen *et al.,* [107], the longer the PF, the higher the splitting tensile strength of the concrete. The results showed that concrete with PF lengths of 42 mm, 54 mm, and 60 mm had a splitting tensile strength of 7.45 MPa, 7.99 MPa, and 8.15 MPa, respectively, when the fibre content was maintained. In general, increasing the content to 1.2% was found to reduce the enhancing effect, leading to the conclusion that the optimal PF content should be below this threshold [97,103,104]. Furthermore, the excessive utilisation of fibre reinforcement has been seen to result in a reduction in the splitting tensile strength when compared to conventional concrete. This can be explained by the fact that excessive PF in concrete weakens the bond between the elements, leading to faster failure than concrete with lower fibre content [37].

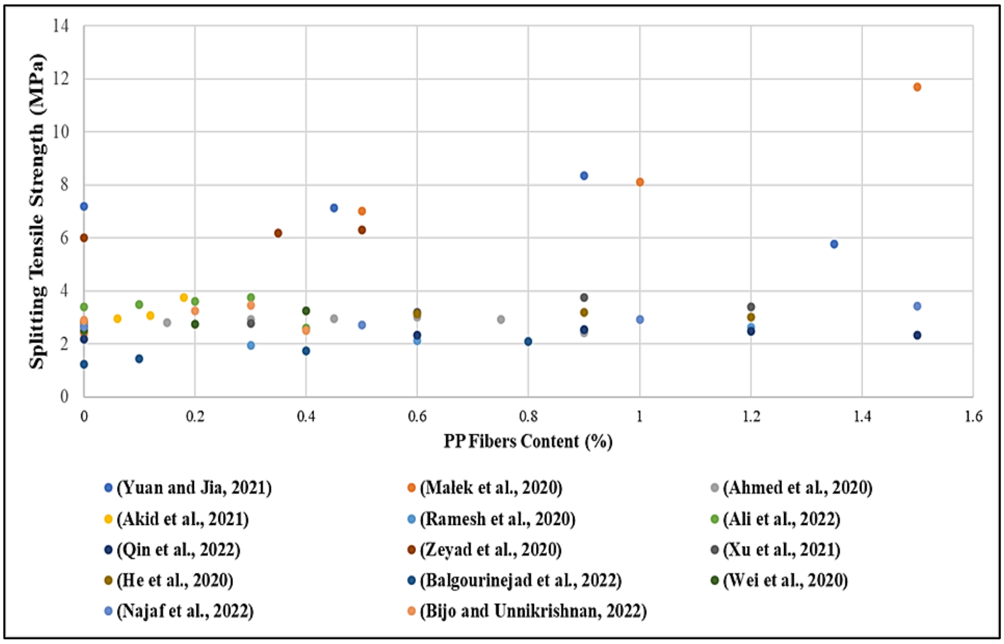

Fig. 6. Effect of PF content on splitting tensile strength of concrete [12,31,57,58,89,92,94,97,102-106]

5.3 Flexural Strength

Figure 7 illustrates the 28-day flexural strength of the concrete changes depending on the PF fraction. Evidently the presence of PF increases flexural strength. When PF is used within a certain range, the flexural strength of concrete increases significantly compared to covenantal concrete. The incorporation of PF has the potential to attenuate or prevent the formation and propagation of initial cracks in fresh concrete and to reduce the stress concentration at the tip of these primary cracks [108,109]. Therefore, it was found that the 28-day flexural strength increases significantly when the PF content reaches about 0.9 %. In another study, according to study conduct by Zeyad *et al.,* [58], compared to normal concrete, the 28-day flexural strength can be increased by up to 40 % if PF is added up to 0.9. The observed increase in 28-day flexural strength with increasing PF content can be attributed to the reduction in the distance between the fibres within the concrete matrix as the volume fraction of PF increases [29].

However, several studies have consistently shown that the optimal concentration of PF is up to 0.6% [12,92,110]. It has been shown that any further increase in concentration weakens the reinforcing effect of PF. It is important to mention that the flexural strength shows a significant improvement when a low PF content is used. An increase in strength between 19.64% and 24.46% is observed when the volume fraction of PF falls in the range of 0.025% to 0.042% [32]. On the other hand, increasing the PF length has a positive effect on the flexural strength of concrete. According to Chen *et al.,* [111] results, it was found that concrete reaches its highest flexural strength of 6.17 MPa when the length of the PF is 12 mm, and the volume fraction is 0.133 %. In contrast, the flexural strength of the concrete decreases slightly to 6.11 MPa when the length of the PF is reduced to 6 mm. In another study, Pehlivanlı *et al.,* [112] reported that the addition of PF to the aerated concrete samples led to a significant increase in flexural strength. Specifically, the flexural strength increased by 25.5% when the fibre length was 3 mm, by 40.8% when the fibre length was 6 mm, and by 49.0% when the fibre length was 12 mm.

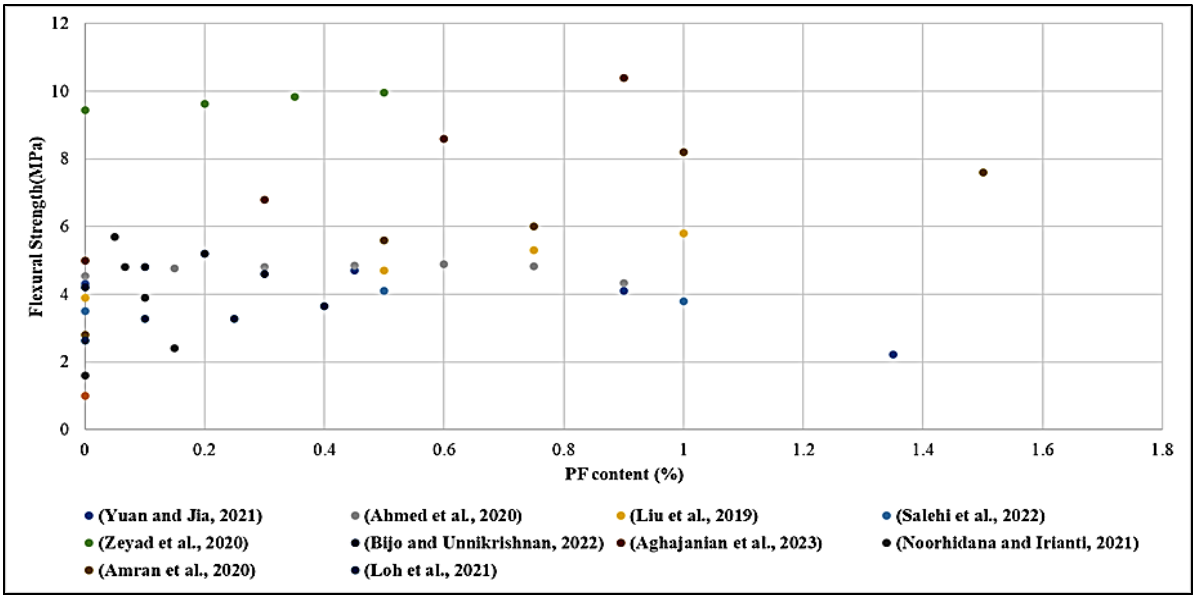

Fig. 7. Influence of PF content on flexural strength of concrete [12,31,46,58,88,92,106,110,113-115]

5.4 Modulus of Elasticity

The Figure 8 illustrates the 28-day modulus of elasticity of the concrete changes depending on the PF content. In general, the presence of fibres has no significant effect on the modulus of elasticity, only a negligible increase or decrease is observed [31,63,94,99,116,117]. According to Suksawang *et al.,* [118], the fibre itself should have no influence on the modulus of elasticity, since discrete fibres cannot clearly withstand compression. However, the effect of PF on the compactness of the concrete is responsible for the variations in modulus of elasticity [94]. Conversely, Zhou *et al.,* [119] claims that recycled aggregate (RA) concrete's modulus of elasticity has a major impact. The findings demonstrated that, in comparison to control samples, the Young's modulus of the mixes containing 0.09%, 0.10%, and 0.11% PP is decreased by 15.52%, 10.15%, and 25.07%, respectively. The authors attributed this to fact that there was a noticeable difference in the micro-hardness of the ITZs, as the new ITZ in RAC had a thicker fibre cement mortar than the previous ITZ. Akça *et al.,* [120] came to a similar conclusion and reported that when the maximum exchange ratio of natural aggregates with RA is reached, there is a decrease of up to 46% if no PF content is present. Compared to the reference value, the loss of modulus of elasticity is up to 62% at the highest RCA and PF concentration.

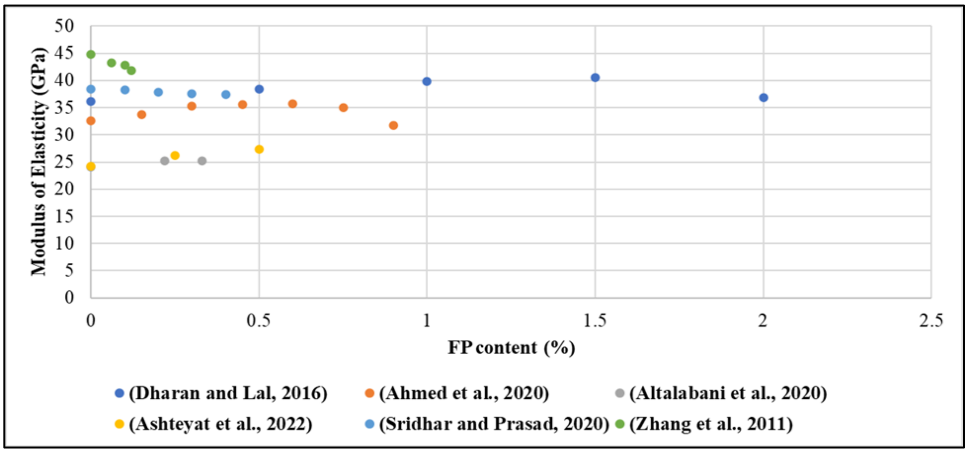

Fig. 8. Influence of the PF content on the modulus of elasticity of concrete [31,70,96,121-123]

6. Durability Properties

6.1 Water Absorption

In general, the addition of PF changes the pore structure, the microcracks and their cross-linking, which affects the water absorption properties of concrete. In this context, several studies have shown that the use of PF reduces the 28 days water absorption of concrete up to a certain threshold [1,12, 99,124-128]. Rashid [126] states that PF-reinforced concrete has lower water absorption values compared to the control mix. At a dose of 0.4 % and 0.6 % PP fibres, the water absorption is reduced by 3 % and 8 %, respectively, compared to the control mix. In a separate investigation, Akid *et al.,* [1] documented that the control mix had the highest water infiltration of 13.5 mm. In contrast, the concrete with 15% fly ash and 0.12% PF had the lowest water infiltration, which was about 27% lower than that of the control mix. The reduction in water penetration depth can be attributed to the inhibitory effect of PF on crack propagation and its ability to reduce the presence of microcracks and impede water flow in the concrete [1]. Figure 9 shows the effects of the additive PF on the different types of concrete.

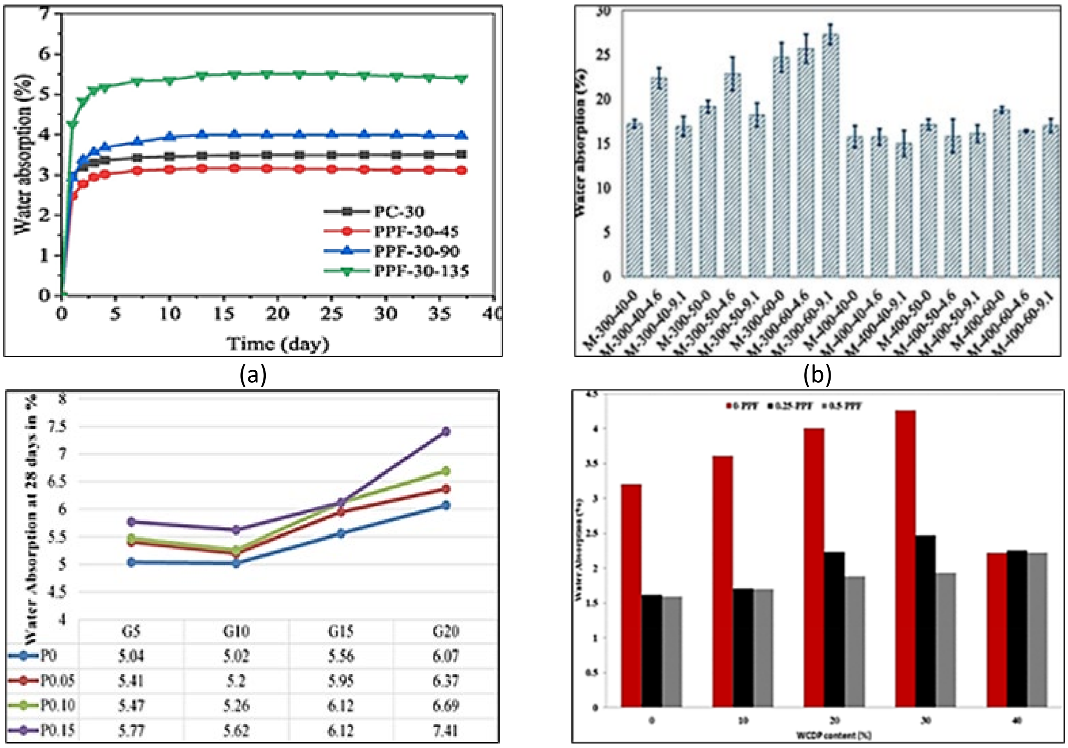

Fig. 9. The effects of additive PF on water absorption properties of different types of concrete (a) Normal concrete [12] (b) Foam concrete [1] (c) Self-compacting concrete [129] (d) Roller-compacted concrete [121]

In addition, the decrease in water absorption can be attributed to the exceptional water barrier properties of PF. Furthermore, the presence of PF in the concrete mixes can lead to limited pore cross-linking and reduced porosity [121]. Nevertheless, the concrete exhibits increased water absorption when the PF concentration exceeds a certain threshold. Afroughsabet *et al.,* [124] claims, for example, that at a PF content of more than 0.45 %. Concrete shows an increase in water absorption. Researchers have come to the same conclusion, but with different threshold values. This can be attributed to the fact that a higher PF content leads to greater inhomogeneity in the internal structure of specimen [130]. On the other hand, alternative studies have shown that the addition of

PF leads to an increase in the water absorption of concrete [58,82,131-133]. The observed result can be attributed to the influence of the PF on the workability of the concrete. The PF led to a reduction in flowability and the formation of additional pores in the concrete mix [58].

6.2 Chloride Penetration

Chloride is the main catalyst for accelerating the corrosion process of reinforcing steel. The penetration of chloride ions into concrete is a very damaging process that significantly impairs the long-term durability and safety of concrete structures [134-136]. Integration of PF reduces the penetration of chloride ions into concrete up to a certain limit over a period of 28 days [1,57,68,128, 130,137-139]. The apparent chloride diffusion coefficient decreases with increasing PF concentration until a certain threshold value [128,140]. Research studies have shown that the addition of a suitable FP content of 0.1% [133,137,138], 0.45% [140], 0.5% [139] and 1% a [68,130] increases the chloride ion resistance of concrete. Mixing a suitable amount of PF can increase the resistance of the concrete to the penetration of chloride ions. This is due to the decrease in the internal conductivity of the pores and the reduced capillary porosity [128,140]. Nevertheless, a further increase in PF content resulted in increased chloride ion infiltration compared to the control mix. This is possibly due to increased permeability [141] and a non-uniform microstructure [129] of the concrete matrix at higher PF dosages. Figure 10 shows the effect of the PF content on the chloride ion resistance of different types of concrete.

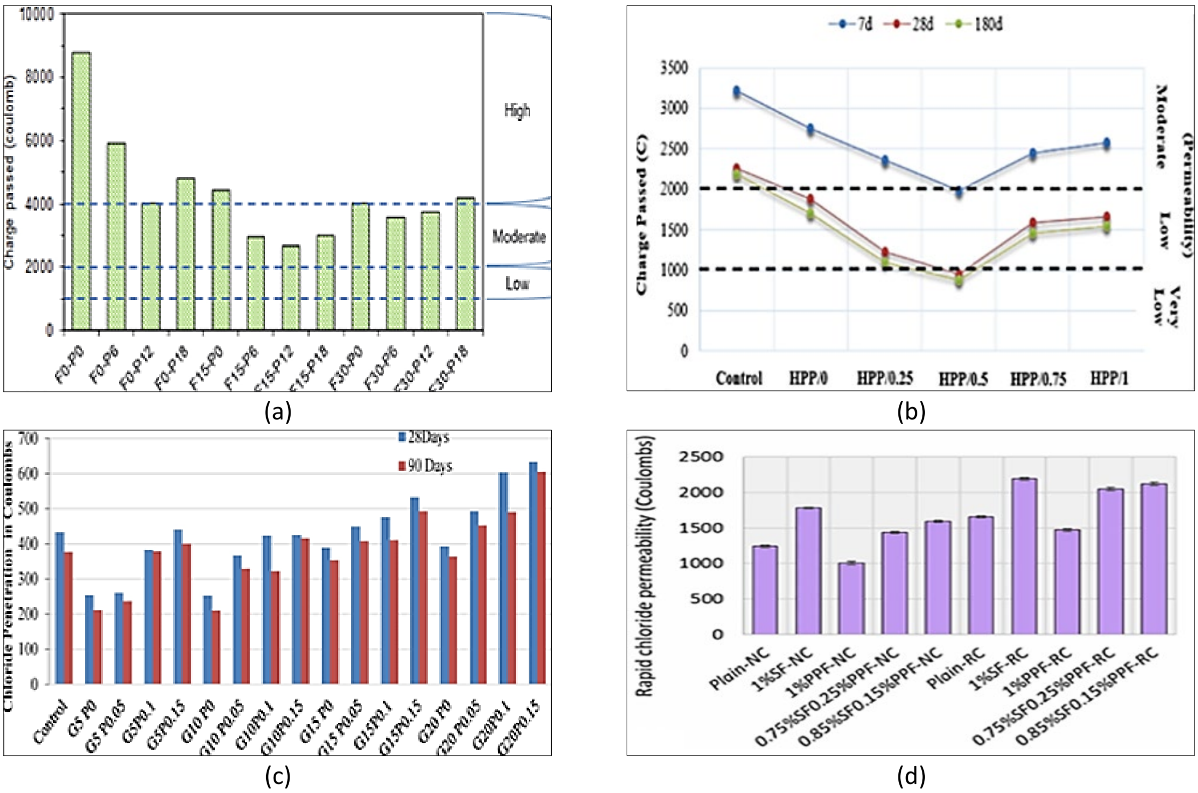

Fig. 10. The effect of the PF content on the chloride ion resistance of different types of concrete (a) Normal concrete [89] (b) Lightweight concrete [139] (c) Self-compacting concrete [133] (d) Recycled aggregates concrete [130]

6.3 Sulphate Attack

The relationship between the addition of PF and the ability to resist expansion caused by sulphate attack becomes clear [142,143]. The inclusion of PF fibres in the mixture significantly reduced the weight gain of the concrete [64,143]. In addition, PF increases the mechanical properties of concrete by keeping the weight constant even when exposed to sulphates [40,127,144]. This phenomenon can be attributed to the close connection between the chaotic distribution of PF and the concrete matrix, which effectively suppresses the formation and propagation of cracks. In addition, the fibres also serve as "bridges" that restrict the growth of pores [144]. In addition, the observed behaviour can be attributed to the increased absorption capacity of the expanding phases in the cavities, which is due to the high concentration of trapped air in PF-containing concrete [145]. Figure 11 illustrates the effect of FP on concrete when exposed to magnesium sulphate.

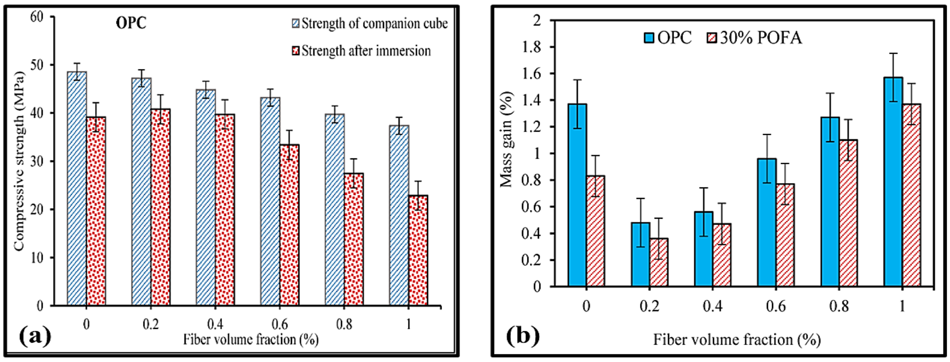

Fig. 11. Effect of PF on concrete when exposed to magnesium sulphate [143] (a) Compressive strength (b) Mass increase

6.4 Drying Shrinkage

In a broader sense, it has been shown that the addition of PF leads to a reduction in the drying shrinkage of concrete [20,35,55,111,146-152]. For example, with a PF content of up to .45 %, the 28 days drying shrinkage was found to be 11 % to 18 % lower than that of the reference concrete [140]. In another study, According to Alrshoudi *et al.,* [146], in the 180-day shrinkage test, the dry shrinkage values for concrete with PF decreased by 11.43 %, 23.3 %, 29.5 %, 16.8 % and 4.5 % for the PF proportions of 0.25 %, 0.5 %, 0.75 %, 1 % and 1.25 %, respectively, compared to the control mix. This could be due to the fact that PF acts as an anti-cracking agent and reduces the drying shrinkage of concrete [131].

On the other hand, Shen *et al.,* [107] asserted that as the length of the PF increased, the utmost total unconstrained strain decreased. The PFs with lengths of 42, 54, and 60 exhibited maximal total free strain values of 151, 140, and 126, respectively. This phenomenon can be attributed to the fact that as the fibre length increases, the interfacial adhesion between the fibres and the concrete increases, which reduces the shrinkage of the concrete [153]. In addition, the use of PF serves to absorb part of the water content and gradually distribute it during the hydration process. Therefore, the inclusion of PF leads to a reduction in shrinkage [133]. Figure 12 presents the effect of the PF content on the drying shrinkage of different types of concrete.

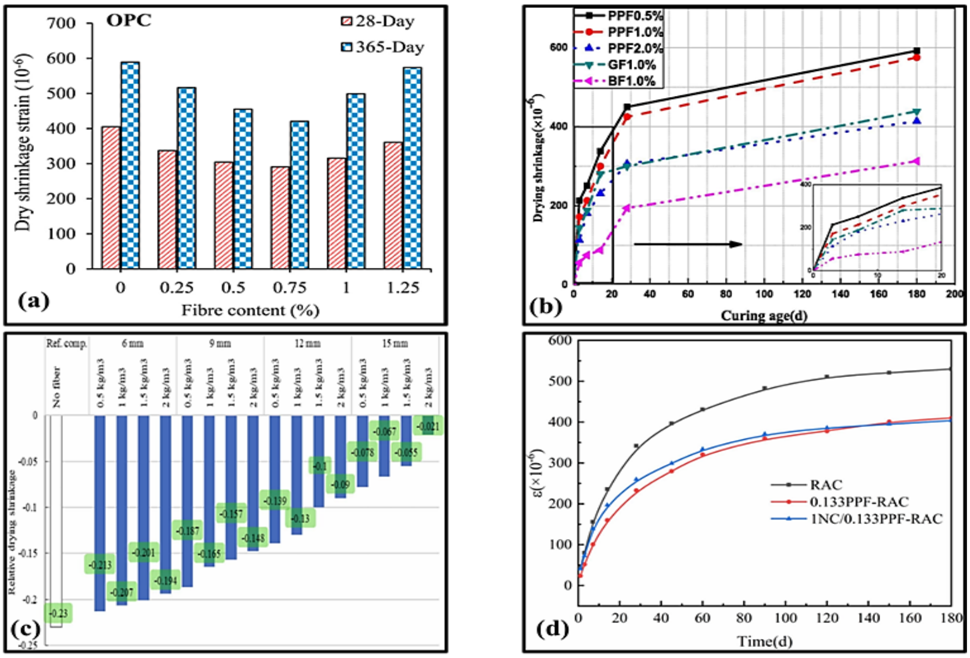

Fig. 12. Effect of PF content on the drying shrinkage of different types of concrete (a) Normal concrete (b) Ultra-high performance concrete [150] (c) Self-compacting concrete [55] (d) Recycled aggregates concrete [111].

6.5 Carbonation Resistance

Use of PF within a certain dose range can effectively mitigate the extent of corrosion caused by carbonation [54,62,152-158]. Addition of a suitable PF content of .1% [157,158], .5% [62,156] and 1% [154] increases the carbonation resistance of concrete. This could be due to the fact that the PF fibres present in the concrete can clog the capillary channels, leading to a reduction in the size of the capillary pores [159]. In addition, the presence of PF in concrete composites has been shown to effectively attenuate cracking, thus reducing the occurrence of microcracks [62,159,160]. Tanash *et al.,* [154] found that the depth of carbonation of concrete initially decreases and then increases with increasing content and length of PF. At a PF volume concentration of 1 % and a length of 12 mm, the depth of carbonation of the concrete after 28 days was only 1.94 mm, i.e., 63.94 % less than that of the reference concrete.

6.6 Fire Resistance

Concrete is used as a building material in construction due to its poor thermal conductivity. However, the limited availability of water and the lack of small pores in concrete lead to an increase in vapor pressure when heated, making it highly susceptible to explosive spalling [154]. PF has a high operating temperature of 1000°C and does not release hazardous compounds at high temperatures. It is an excellent material to resist fire as it has enlarged pore spaces that are created when PF melts in a fire, alleviating pore pressure [155]. The addition of PF to concrete increases its strength at various elevated temperatures and reduces the loss of strength caused by rising temperatures [50,159]. In addition, the use of PF on concrete often reduces the occurrence of concrete spalling at high temperatures [160,161]. This could be due to the reduction in pore pressure when PF is incorporated into concrete at high temperatures [160]. This decrease in pore pressure is attributed to the low melting point of the PF fibres, which form a percolation system in the concrete matrix [162].

7. Conclusions

Conclusively, research into PF as concrete additive is gaining popularity due to its ability to resist cracking in concrete and maintain its performance at extreme temperatures. Concrete demonstrates a reduction in workability with incorporation of large PF dosage. Optimal use of PF from 0.1% to 0.6% can improve the compressive strength of concrete via its crack resistance. However, excessive use needs to be avoided as it would reduce homogeneity of concrete mix and lower the strength. Use of PF 0.6% to 0.9% enhances splitting tensile strength of concrete owing to microcrack resistance. Modulus of elasticity is not affected due to integration of PF unless it is excessive integrated in the mixture. The water absorption of concrete may be effectively decreased by using PF optimally. The resistance of concrete against sulphate and chloride attacks increases with the addition of a suitable dosage of polypropylene fibres. The blending of fibres in concrete mixtures that makes the concrete denser enhances its fire resistance properties.

There is research areas related to the use of PF in concrete that remain to be explored. The structural performance and fire resistance of concrete produced using binary or ternary blend of PF fibre, steel fibre, glass fibre, kenaf fibre should be investigated. The mechanical and durability properties of agricultural ash blended cement concrete containing PF remain to be explored. The performance of concrete produced through integration of mixed PF with kenaf fibre and bamboo fibre is another area to be looked into. The durability performance of self-compacting lightweight aggregate palm oil fuel ash blended cement based concrete containing PF of diverse size and ratio in another interesting area to be explored. The impact of PF integration on performance of 3D printing concrete, heavy weight concrete, polymer concrete, pervious concrete and other modern concrete remain to be discovered in future.

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