IRAQI Academic Scientific Journals

Tikrit Journal of Engineering Sciences (2020) 20 (3): 82-97.

ISSN: 1813-162X (Print) ; 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

Ahmed TW, Aljubory NH, Zidan RS. Properties and Performance of Polypropylene Fiber Reinforced Concrete : A review. *Tikrit Journal of Engineering Sciences* 2020; **20**(3): 82- 97.

Properties and Performance of Polypropylene Fiber Reinforced Concrete : A review

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***Keywords*:**

Polypropylene fiber, Recycled aggregate concrete, Hybrid fiber concrete.

ARTICLE INFO

Article history:

Received	03 Apr. 2020
Accepted	25 Oct. 2020
Available online	01 Jan. 2021

A B S T R A C T

The (brittle) behavior of concrete, although used in many fields, impedes its use in some applications that require (flexible) behavior, wherefore several types of fibers were utilized among them polypropylene fiber (PPF), that enhances pre-crack tensile strength, toughness, ductility performance, impact resistance, flexural strength resistance, and failure mode. This paper submits a comprehensive review of previous studies that discussed the properties and performance of utilizing PPF in normal and high strength concrete, recycled aggregate concrete and hybrid fiber concrete.

DOI: http://dx.doi.org/10.25130/tjes.27.2.10

خصائص و أداء الخرسانة المسلحة بألياف البولي بروبيلين: مراجعة

تقى وليد أحمد / قسم الهندسة المدنية/ كلية هندسة / جامعة الموصل
نهى حميدي الجبوري / قسم الهندسة المدنية/ كلية هندسة / جامعة الموصل
رؤى سهيل زيدان / قسم الهندسة المدنية/ كلية هندسة / جامعة الموصل

الخلاصة

إن سلوك الخرسانة (الهش) على الرغم من إستخدامه في العديد من المجالات يشكل عائقا يحول دون إستخدامه في بعض التطبيقات التي تتطلب سلوكا (مرنا) ولذلك تم إستخدام أنواع عديدة من الألياف من ضمنها ألياف البولي بروبيلين التي تعمل على تحسين مقاومة الشد المسبق للصدع و الصلابة و المطاوعة والإنثناء ومقاومة الصدم و نوع الفشل. يقدم هذا البحث إستعراضا شاملا للدراسات التي أجريت مؤخرا والتي ناقشت خصائص وأداء إستخدام ألياف البولي بروبيلين في الخرسانة العادية والعالية المقاومة وخرسانة الركام المعاد إستخدامه وخرسانة الألياف الهجينة.

الكلمات الدالة: الياف البولي بروبيلين, خرسانة الركام المعاد إستخدامه, خرسانة الألياف الهجينة.

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1. INTRODUCTION

In the civil engineering field concrete is a vastly used substance. However, it is propounded low ductility and less tensile characteristics therefore incorporating fibers (discontinuous and separated) like polypropylene fiber (PPF) can ameliorate these properties principally the tensile strength. In 1965, PPF was suggested for use as a concrete admixture for (blast resistant) buildings for engineers of US Corps. Posteriorly, the use of PPF has been reformed and applied now for thin sheet consistency or as short reinforcement fiber in concrete. Hence, almost 4 million tons of PP every year were produced in the world. In production, PP takes the fourth level after polyesters, polyimides, and acrylics. Additionally, PPF applications have been enlarged because of their benefits to concrete especially enhancing tensile, flexural strength and concrete failure mode [1]. Three types of PPF are available monofilament, fibrillated and microfilament Fig. 1; the production of the 1st form is done via an extrusion process by spinneret puncture. After that, they were severed to the coveted length. The production of the 2nd newest form (film) is similar to the first but the PP is extruded via a die-which induces flat film or tubular, after that the film is punctured into tapes and stretched uniaxially. A roller pin system was molded to stretch these tapes over them neatly and hence longitudinal splits will generate and severed or twisted to fabricate different types of fibers (fibrillated). Like physical structures, the fibrillated type gain a grid, via the extruding operation the molecular orientation produced will improve the fiber's tensile strength. Monofilament PPF type is introduced as (additives) in reinforced concrete as 1st kind of PPF. Monofilament is generated by (twisted) or (end buttons) formations to give the best performance and better anchorage. Microfilament PPF type like monofilament but with less length and tensile strength [2].

(a) (b) (c)

Fig.1. Types of PPF: a) Monofilament b) Fibrillated c) microfilament.

Fibrillated PPF type is generated in bundles or collated jointly and available with 0.5, 0.75 and 1.5 or 2 inches lengths. Many producers recommended this type for paving applications. (Blended collated) or (Twisted collated) as shown in Fig. 2 are another types of fibrillated PPF with 0.75 to 2 inches lengths. During the mixture, the twisted collated submits the best 3D distribution [1].

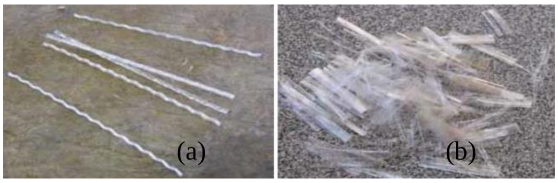
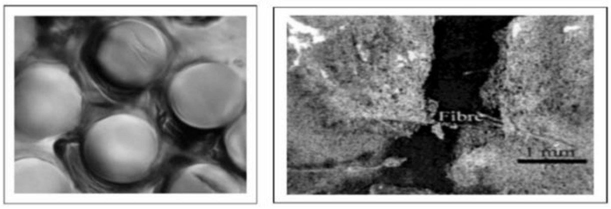


Fig. 2. a) Twisted wave geometry and b) Mesh geometry [1].

The nature of the production of PPF makes it with many benefits, i.e. PPF material is derived from monomeric C_3H_6 that is a pure hydrocarbon. The combination of polymerization mode and the weight of the augment molecular also the attitude converting them to the fiber producing PPF have many advantages among them; low thermal conductivity and renitence to chemicals, alkalis, and acids and hence better durability with cost efficiency [3,4]. The wet surface of PPF is not affected by the cement paste helping the chopped fiber not to ball when mixed, also the film will be weak in a lateral direction by the orientation expedite fibrillations, therefore a mechanical connection will be created between the fibers and matrix [2]. Fig. 3 shows the SEM of the fiber cross-section and fiber action through flexure text.



(a) (b)

Fig. 3. a) SEM of the cross-section of PPF and b) The fiber slipping action through flexural strength test [5].

The concrete structures can be changed by cracks that convert them into permeable ingredients which lead to corrosion risk, also they can be out of service. PPF can eliminate crack problems by reducing crack width, accordingly qualifying further opening. Additionally, PPF has (165° C) melting point, and above (100° C) temperatures can hold for (few times) before (softening) and it can be disadvantaged by Oxygen and UV radiation, but this issue is negated inside concrete matrix [1,2]. This comprehensive study illustrates the properties and performance of utilizing PPF in normal and high strength concrete, recycled aggregate concrete and hybrid fiber concrete.

In order to be the reference for future studies concerning this fiber type.

2. PREVIOUS STUDIES

2.1. Normal and High Strength Concrete with PPF.

Many previous studies were employed with different PPF dosages for investigating the effect of this fiber on several parameters. Table 1 shows the summary of these studies.

The slump test represents essentially the work of the concrete mix. The inclusion of more PPF ratios decrease the value of the slump due to more clingy mixture which causes adhesion and cohesion in fresh concrete, the aggregate motion shears solo the fiber during the mixing, which forms a linked fibers network anchor to the cement paste by their high specific area [1, 14, 15, 18, 24]. The increase in the PPF volume ratio leads to a reduction in the degree of compaction thus increasing the air volume amidst the mix and hence water absorption increment and density decrement of concrete at mature situation [4, 13, 21, 24]. The mixes containing silica fume and/or PPF presented a negative impact on concrete workability [25].

The inclusion of fly ash enhanced the concrete workability, but the addition of PPF reduced it, also the PPF mixes with or without fly ash have lesser unit weight compared with no fiber mixes [7], Tables [2,3] represent concrete mixes and fresh properties respectively.

Table 1. Summary of the previous studies explaining PPF role for normal and high strength concrete.

References	Properties	Comments
[5]	(0.1% and 0.3%) volume fractions of both (12 and 19 mm) length of monofilament PPF into (M40) grade concrete.	The results showed non presumed effect for compressive strength by fiber usage but an enhancement for durability parameters, toughness index, flexural and tensile strengths were reported by fiber usage, also after analytical and experimental tests, it was found that crack width decreased by fiber length (with or without) decrement of fiber diameter.
[6]	(0%, 0.2%, 0.3% and 0.5%) by volume of (12 mm) length with (8%) silica fume.	15% enhancement in compressive strength for 0.5% PPF after 91 days compared to the reference mix, the addition of silica fume promotes the dispersion of fiber in concrete mix and raised the compressive strength by 30%. The tensile and flexure strengths were also enhanced. The addition of silica fume into no fiber mix leads to brittleness while for the fiber mix a ductile failure was observed.
[7]	(0%, 0.05%, 0.1% and 0.2%) fibrillated PPF by volume into concrete containing (0%, 15% and 30%) by mass of fly ash.	PPF and fly ash minimized concrete unit weight; the compressive strength decreased by increasing fly ash replacement and PPF ratios. Fly ash increases porosity, sorptivity coefficient value and water absorption but the influence of fly ash on the sorptivity coefficient is more pronounced than the PPF. Also, they are reducing drying shrinkage. It was found that the effect of fly ash is more pronounced for freezing-thaw resistance than the PPF effect and the resistance increased with fly ash content increment.
[8]	(0%, 0.15%, 0.2%, 0.25%, 0.3%, 0.35% and 0.4%) PPF triangular type of (12 mm) length into (M30) concrete grade.	An enhancement up to 0.3% of PPF for compressive strength (from 33.36 N/mm^2 to 50.1 N/mm^2) at 28 days. The PPF enhanced the durability attribute of concrete besides weight loss.
[9]	(0%, 0.2%, 0.3% and 0.5%) volume fraction of (12mm) length into HSC containing (8%) silica fume by weight of cement.	The long-term compressive strength increased with PPF and silica fume addition, also the samples containing silica fume have resistance to electricity but the inclusion of PPF decreases it slightly. The absorption of water for samples with silica fume and PPF decreased principally when compared to reference samples. Finally, the results of dynamic frequency not having considerable effect by PPF and silica fume inclusion.

[10]	(0.06%, 0.08% and 0.12%) volumetric ratios of PPF into concrete containing 6% silica fume and 15% fly ash.	PPF had a small adverse effect on the workability but also improved the durability clearly. There was also an increase in fiber concrete properties like a strain of dry shrinkage, water permeability length and the carbonation depth of concrete compared to those that do not contain fibers. Finally, the freeze-thaw resistance was improved by up to 0.08%.
[1]	(0%, 0.5%, 1%, 1.5% and 2%) of PPF in (M30 and M40) concrete.	0.5% PPF was the optimum ratio, also PPF contracted the moisture loss and shrinkage of concrete mixtures at sooner days finally, by increasing the volume of PPF the workability was reduced.
[11]	(0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3%) monofilament macro PPF of (35 mm) length into (M25) and (M30) grade concrete containing 5% fly ash.	The optimum value was 1% which gave maximum compressive and tensile strengths for (M25) grade 12.15% and 2.81% respectively, and for (M30) grade 8.34% and 9.63% respectively.
[12]	(1.5% PPF of 20 mm length) and (0.75% PPF of 12 mm and 0.75% PPF of 20 mm length) into geopolymer concrete includes alkaline liquids and fly ash.	Compressive, split and flexural strengths of PPF geopolymer concrete increased compared with the control one (without PPF), the maximum increment in compressive, flexural and split tensile strengths were obtained for 1.5% PPF of (20 mm) length that gave (8.483%, 19.25% and 12.26%) respectively when compared to the control one.
[13]	(0%, 0.5%, 1%, 2%, 3%, 4% and 5%) by volume of PPF in fly ash-based geopolymer composites concrete.	PPF addition up to 3% of weight into a paste of geopolymer detracted the shrinkage and augmented composite's energy absorption, while it might minimize the ultimate compressive and flexural strengths according to the fiber ratio.
[14]	(0.2, 0.3, 0.4 and 0.5) % volumetric ratio of PPF (recon3S) in M35 grade concrete.	By increasing fiber ratios, there had been a decrease in slump results. Also, the ratio (0.3%) of PPF increased the tensile strength from 2.65MPa to 3.4 MPa after 28 days of curing. More fiber addition after 0.3% value showed a decrement in flexural strength from 6.38 MPa to 2.65 MPa.
[15]	(0%, 0.1%, 0.3% and 0.5%) by volume of monofilament PPF of (12 mm) length.	Concrete workability decreases with more additional ratios of PPF and by increasing the percentage of PPF, the modulus of elasticity decreased by about 2% to 9%. Also, the flexural strength increased by 9% for 0.5% PPF and the splitting tensile strength enhanced by 25% to 42% while no effect was observed for compressive strength results.
[16]	(0%, 1%, 1.5% and 2%) PPF, type monofilament of (18 mm) length into (M26) grade concrete.	The maximum compressive strength was obtained for (1.5%) PPF where the increment was from (26 to 29.5) N/mm^2.
[17]	(0%, 1%, 1.5% and 2%) PPF, type monofilament of (6mm) length into (M25) grade concrete.	The results revealed that the compressive strength increases from 4% to 12% with the addition of PPF compared with the control mix, and with the increase in fiber ratio a reduction in slump value was noticed.

[18]	(0.5%, 1%, 1.5% and 2%) PPF blended type of (24, 40, and 55 mm) length into (M30) concrete grade.	1.5% PPF gave the maximum strengths were for (compressive strength the superfast was 17%, 22% for split tensile strength and 24% for flexural strength) compared with no fiber mix, also the study showed a reduction in workability with the increase in fiber volume due to the formation of air voids.
[19]	(1%, 1.5%, and 2%) by weight of cement of monofilaments PPF of (12mm) length into (M45) grade of concrete.	The optimum ratio was found to be 2% that gave 15% compressive strength higher than the control mix, also the flexural and tensile strength increased.
[20]	(0.5%, 1%, 1.5% and 2% by weight) of PPF to double Tee beams.	An enhancement in general in concrete properties, load-bearing capacity, ductility, control cracking and shear strength by fiber addition. The highest value for deflection deficient was 21.47% and the deflection was increased by adding more dosage of fiber.
[21]	(0%, 0.1%, 0.2%, 1% and 2%) volume fractions of PPF (12 mm) length into (M20) grade concrete.	The increments in compressive and flexural strengths were (9.8% and 16%) for 0.2% (optimum ratio) at 28 days. It was mentioned that the water absorption was maximized by maximizing PPF proportions that where for (0% - 2%) PPF the increments were (3.9% - 9.3%) respectively.
[22]	(0%, 0.5%, 1%, 1.5% and 2%) volume fractions of PPF (12 mm) length into (M25) grade concrete.	The optimum ratio was 1% which attains (7.76%) increase in compressive strength and (26.57%) increase in split tensile strength, while (33.61%) is the maximum flexural strength that was for 2% PPF. After 1% the results were decreased and a reduction in flow and slump was recorded by more fiber addition, from that they conclude a considerable enhancement in flexural and splitting tensile while the incommensurate effect for compressive strength was found.
[23]	(0.5%, 1%, 2%, 2.5%, 3% and 3.5%) PPF of (6mm) length into concrete containing two replacement ratios with high performance cement (10% and 20%).	Well improvement by this combination, the enhancement in compressive strength was from (30.1 to 42.9) MPa, the tensile strength from (1.9 to 7) MPa and flexural strength from (2.7 to 14.5) MPa. Also, the modified mix by PPF and high-performance cement showed adequate strength for counteracting addition load cycles after 1st failure load release Fig. 4 shows the failure of samples under various cycles of load.
[24]	(0.06% to 2.16%) PPF of (12mm) length into (M40) grade concrete.	(0.36%) was the optimum value, where an improvement of 18%, 14% and 16% in compressive, flexural and tensile strengths were recorded. For more higher fiber proportions; the density was decreased and water absorption was increased and at 0.96% and more, the slump value has vanished.

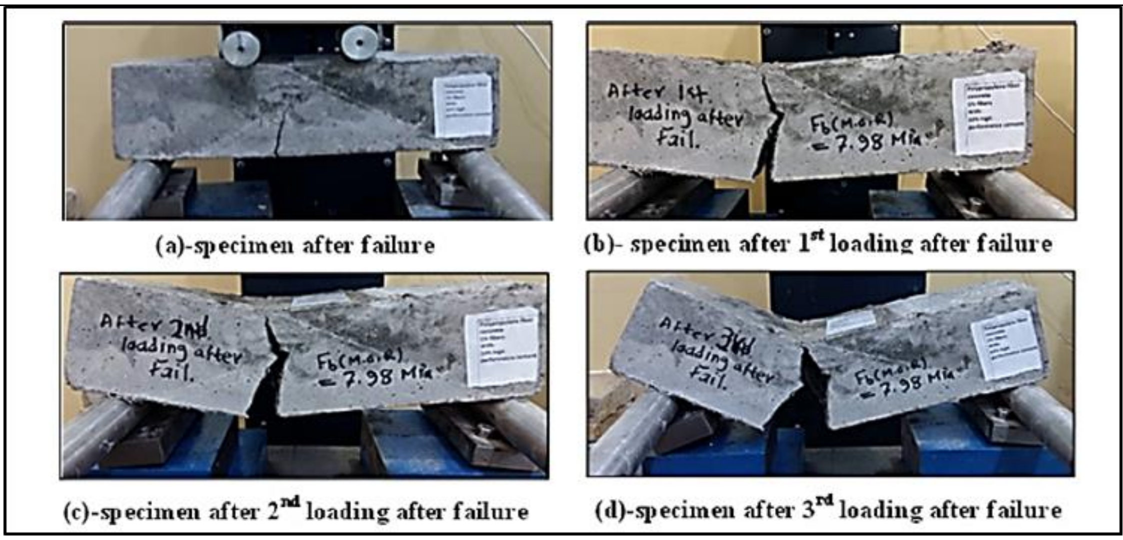


Fig. 4. Concrete samples of PPF after failure for various cycles of load [23].

Table 2. Concrete mixes [7].

Mixure	PC (kg/m^3)	FA (kg/m^3)	PP fiber (kg/m^3)	W (lt/m^3)	HP (kg/m^3)	Aggr. (kg/m^3)
A1	400	-	-	140	4.0	891
A2	400	-	0.45	140	4.0	1890
A3	400	-	0.90	140	4.0	1889
A4	400	-	1.80	140	4.0	1886
B1	340	60	-	140	4.0	1874
B2	340	60	0.45	140	4.0	1872
B3	340	60	0.90	140	4.0	1871
B4	340	60	1.80	140	4.0	1868
C1	280	120	-	140	4.0	1856
C2	280	120	0.45	140	4.0	1855
C3	280	120	0.90	140	4.0	1853
C4	280	120	1.80	140	4.0	1851

The fiber impact on concrete strength has been related to the fiber proportions, length, aspect ratio and also fiber tensile strength [26].

While some studies showed a non-presumed effect on compressive strength using PPF [5, 15] the others showed an enhancement [9, 21, 23, 1, 8, 19]. Where for the addition to the normal concrete the maximum compressive strength increment was from (26 to 29.5) N/mm^2 for 1.5% PPF was recorded by Alsadey [16] and by Alsadey and Salem [17] was from (4% to 12%) for (1%-2%) PPF. In addition, Darhan and Lal [18] recorded 17% for 1.5% PPF (blended type) and 18% for 0.36% PPF. An increment of 30% was recorded by Nili and Afroughsabet [6] for (8% silica fume) incorporation and 0.5% PPF at 91 days which reflects the pozzolanic impact of silica fume and fiber crack constraint. Khan et al. [11] recorded (12.5%) increment for (M25 grade) via adding 1% PPF and 5% fly ash, while (8.34% for (M30 grade). However, Karhan and Atis [7] noticed a compressive strength decrement by increasing fly ash replacement fiber ratios. Like compressive strength, the split tensile and flexural strength increases by the PPF ratio increase to a certain limit then decreases due to the generation of voids inside the concrete mix [6, 5 15, 24].

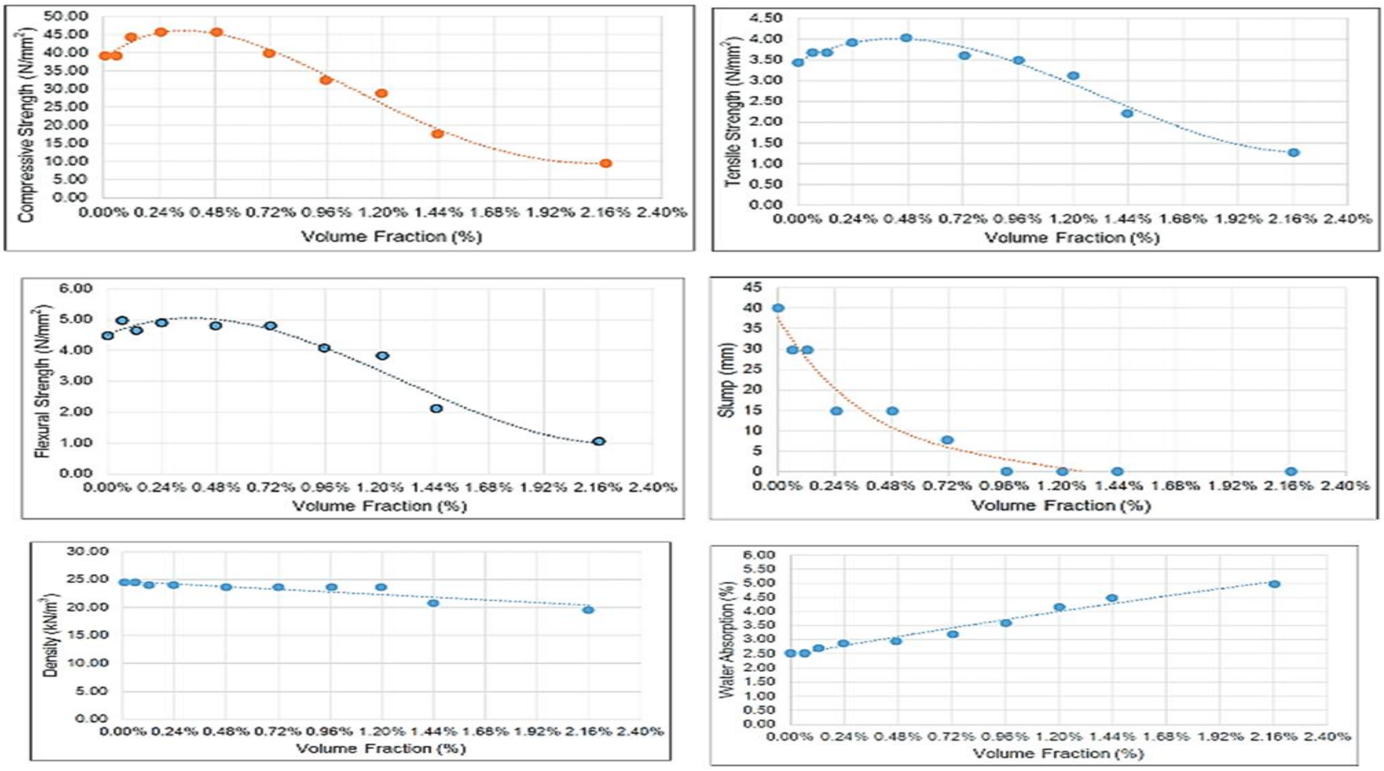


Fig. 5. Concrete fresh and hardened properties [24].

Table 3. Fresh properties [7].

No.	Density (kg/m^3)	V-B(s)	Slump(cm)	No.	Density (kg/m^3)	V-B (s)	Slump(cm)	No.	Density (kg/m^3)	V-B (s)	Slump(cm)
A1	2540	6.0	17	B1	2519	3.1	18	C1	2492	2.5	19
A2	2533	7.0	17	B2	2507	5.6	18	C2	2489	4.9	19
A3	2524	8.0	16	B3	2501	6.5	16	C3	2486	5.6	16
A4	2513	10.0	14	B4	2492	7.8	15	C4	2480	6.7	15

Patil and Patil [12] recorded flexural and tensile strength amelioration by 19.25% and 12.26% for 1.5% PPF of (20 mm) length in geopolymer concrete, where for 24% and 22% for 1.5% PPF (blended type) as mentioned by Dharan and Lal [18] while (26.57%) increment of tensile strength for 1% PPF and 33.61% of flexural strength for 2% PPF [22]. 0.4% PPF and 10% silica fume gave the optimum flexural strength where the improvement was about 41% compared with the reference mix as obtained by [25]. Fig. 5 illustrates the effect of PPF on the concrete fresh and hardened properties [24]. The existence of PPF reduced the dry shrinkage of concrete and by the combination with the fly ash the reduction was increased, while the resistance to freeze-thaw was increased by the presence of PPF, but the effect of fly ash was found to be more than PPF. The values of porosity, sorptivity coefficient and water absorption were increased by PPF and/or fly ash increment [7]

Also, the capacity of impact load has been modified by PPF incorporation [27]. The PPF ratio augmentation lessened minimally the electrical resistivity [6, 9] and for concrete having silica fume and fly ash diminished the dry shrinkage and carbonation depth but somewhat increase the freeze-thaw resistance [10]. An influential reduction in capillary porosity obtained by sorptivity test via utilizing PPF in concrete and this has a good impact on the reinforced concrete structures durability, besides, a linear trend with strong correlation was obtained between PPF volume fraction and initial sorptivity median, also, it was mentioned that PPF enhanced concrete surface abrasion remarkably [28]. The compressive strengths versus their PPF ratios of several studies are shown in Fig.6. From this figure, it can be concluded that the highest compressive strength values lie approximately in the range of (0.3-0.5).

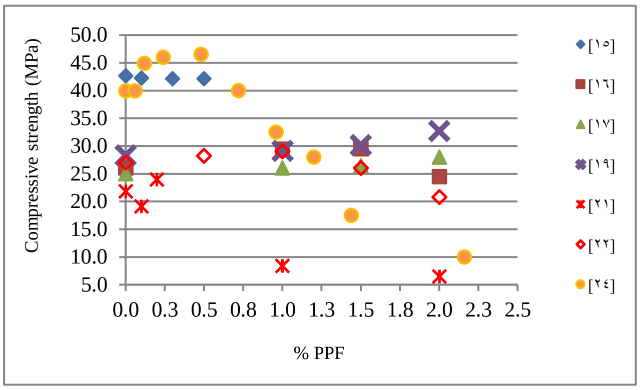


Fig. 6. Compressive strength of concrete for several previous studies.

2.2. Recycled Aggregate (RA) Concrete with PPF.

Many previous studies discussed the use of PPF in recycled aggregate concrete; Table 4 shows the summary of these studies.

Table 4. Summary of previous studies explaining PPF role for recycled aggregate concrete.

References	Properties	Comments
[29]	PPF incorporation (9 kg/m^3) of (30 mm) length into RA concrete with (30% and 50%) replacement with natural aggregate (NA).	The compressive and tensile strength of 30% RA changed from (26.74 to 28.21) MPa and (2.63 to 2.49) MPa using PPF respectively and for 50% RA from (25.02 to 34.98) MPa and (2.64 to 2.67) MPa using PPF respectively.
[30]	RA from the devastated buildings with (0%, 15%, 25% and 35%) replacement with NA into (M20 grade) concrete containing 57.6 (Kg/m3) PPF of (6mm) length.	The addition of PPF improved the compressive and tensile strength where the maximum compressive strength value was found (35.74 N/mm^2 for 35% RA) while the tensile strength was enhanced from (1.21 N/mm^2 to 5.47 N/mm^2) at 7 and 28 days respectively. Fig. 7 shows the used shape of PPF and recycled aggregate.
[31]	(0%, 0.3%, 0.6%, 0.9%, 1.2% and 1.5%) PPF fibrillated type of (15 mm) length, to the treated and untreated RA (60%) replaced with NA collected from debris area.	The compressive strength increased till 0.6% PPF then decreased, while the maximum value of flexural strength was at 0.15% PPF the total porosity and water absorption results were eliminated by PPF inclusion in RA concrete.

[32]	(0%, 0.1% and 0.15%) PPF by weight of cement of (10 mm) length with RA of (0%, 5% and 10%) replacement with NA.	An increment of concrete mechanical properties with PPF ratio increase, and the maximum values for test parameters obtained for 0% RA and 0.15% PPF.
[33]	(0%, 0.5%, 0.75% and 1%) PPF with 100% RA in (M25) grade concrete.	0.5% PPF gives the maximum values for all test parameters. The increments were (4.46% and 4.25%) of compressive strength for NA and RA concrete, while for split tensile strength the increments were (18.01% and 10.25%) for (NA and RA) concrete also for flexural strength, the enhancements were (17.15% and 12.26%) for (NA and RA) respectively.
[3]	(0.5%, 0.75% and 1%) volume fraction of microfilament PPF (12 mm) length in both normal and 100% RA.	0.5% is the optimum fiber content at which (17.15% and 12.01%) enhancement of flexural and splitting strength for RA concrete, while for compressive strength the fiber effect was negligible, and it was noticed that the fiber effect is more prominent for NA concrete compared with RA concrete in strain enhancement Figs. 8 and 9.
[34]	(1% and 2%) of PPF (47 mm) cut length into RA concrete by replacement ratios with NA (0%, 25%, 50%, 75%, and 100%).	The compressive strength has improved for the RA concrete and the highest limit of RA concrete with 1% PPF is allowed to be 50% and for 100% RA with 2% PPF the increment in (compressive strength was 15.68%), (split tensile strength 34.84%), and for (shear strength was 38.32%).
[35]	(0%, 0.5%, 1%, 1.5%) triangular type PPF of (12mm) length with (0%, 15%, 30%, and 45%) RA replaced with NA into (M40 grade) concrete.	The strength demand for concrete was achieved by incorporating PPF and (15% and 30%) RA, thus it can be utilized in any general construction. However 45% RA concrete with PPF can be utilized in structures of no load-bearing also in pavement construction.
[36]	(0%, 0.2%, 0.3%, 0.4%) triangular type PPF of (6-12mm) length with (0%, 50%, and 100%) RA replaced with NA into (M60 grade) high strength concrete.	By increasing both proportions of RA and PPF a decrement in workability was noticed, and an enhancement in compressive strength, secant modulus of elasticity and tensile strength was recorded for 0.2% PPF. Also, utilizing up to 50% RA is adequate for producing high strength concrete (M60 grade).
[4]	(0%, 0.15%, 0.3%, 0.45%, 0.6%, 0.75% and 0.9%) PPF of (6 mm) length, into HSC containing 10% silica fume and (0%, 50% and 100%) RA.	The mechanical properties were intensified by the addition of PPF up to 0.6% which is the optimum fiber ratio. Also, the design operators of optimum solutions were obtained.

(a) (b)

Fig. 7. **(**a) Polypropylene fiber (b) Recycled aggregate [30].

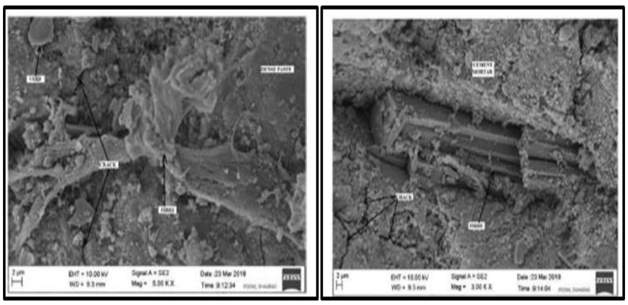


Fig. 8. FESEM images of PPF in RA concrete [3].

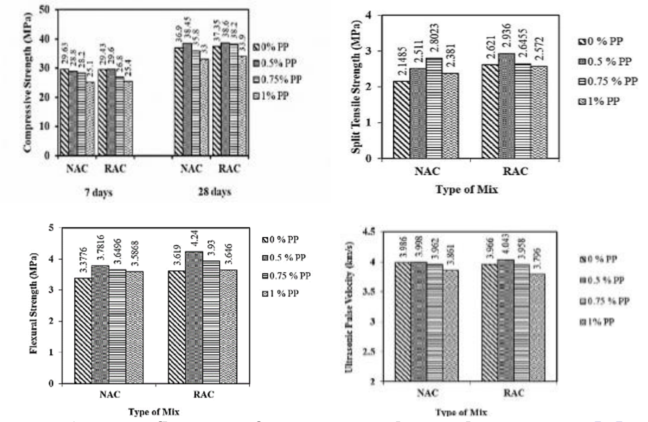


Fig. 9. Influence of PPF on mechanical properties [3].

The use of RA in concrete minifies the strength, density and durability and magnifies dry shrinkage, water porosity and creep [37-40]. Therefore many types of research were endeavored to enhance the RAC characteristics by supplying mineral additives [41, 42], or by applying several treatments or using fibers [4, 31, 43, 44]. The concrete workability decreased by utilizing both (PPF and RA) but the desired one can be achieved via utilizing superplasticizer admixture, the same behavior was recorded for concrete unit weight [4, 45]. The concrete strength count on aggregate or fiber strength, the cement matrix and on the interfacial transition zone between the matrix of cement and the aggregate or fiber [41]. The mechanical characteristics weakened by increasing the ratio of RA, but the presence of PPF has enhanced the properties to a certain limit of fiber and then decreased due to plump out of the fiber. Where in some cases the increment was minimal [3, 46] while in others was significant [4, 33, 34]. Kumar et al. [47] recorded the possibility of high strength concrete reproduction by 1% PPF and 25% RA, also PPF utilization caused elasticity improvement and crack elimination of shrinkage [47]. The permeability and mechanical characteristics were modified by treated RA usage but the inclusion of PPF was ameliorating the findings [31]. The addition of PPF leads to cracks occurrence among the loading points before sample failure, also by increasing the PPF proportions the deflection was minimized at the same load. Fig. 10 shows the beam deflection variation with load for 100% RA [36].

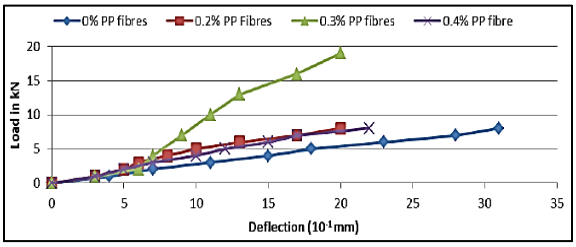


Fig. 10. Beam deflection variation with load for 100% RA [36].

Akça et al [45] found that the RA type in concrete having PPF and RA affected the mechanical characteristics more than other factors [45]. The concrete strength count on aggregate/fiber strength, the cement matrix also on the interfacial transition zone between the matrix of cement and the aggregate/fiber [41]. Moreover, the total porosity results as shown in Fig. 11 were eliminated by PPF incorporation in RA concrete with age because voids and cracks in concrete were bridged through PPF hence decreasing the porosity with time [35].

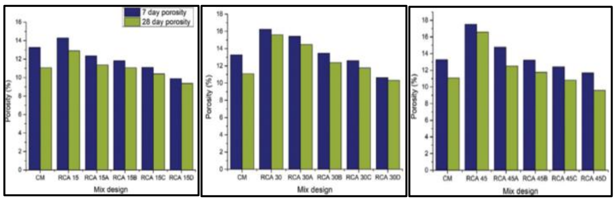


Fig. 11. Porosity variations with %PPF and age for (15%, 30% and 45%) RA respectively [35].

From the previous studies, it can be concluded that the highest values of compressive strength for 100% RA replacement as an example have approximately between (0.3%-0.6%) of PPF proportions as shown in Fig. 12. Despite numerous researches, there is a shortage of studies concerning the durability of RA and PPF reinforced concrete. The authors, therefore, suggest scrutinizing further durability tests in this field, i.e. permeability and rapid chloride penetration tests.

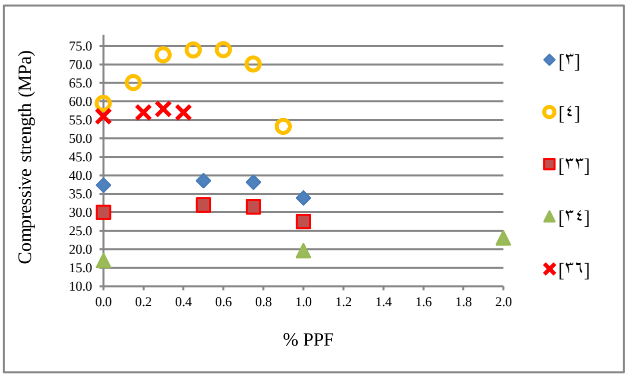


Fig. 12. Compressive strengths of 100% RA concrete for several previous studies.

2.3. Hybrid Fiber Reinforced Concrete Including PPF.

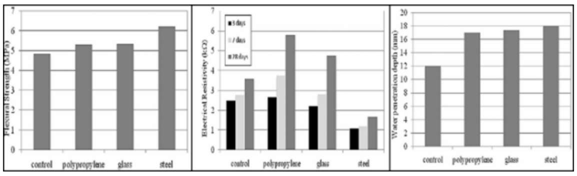
Many previous studies discussed the use of PPF in hybrid fiber reinforced concrete; Table 5 shows the summary of these studies.

Table 5. Summary of previous studies explaining hybrid fiber reinforced concrete including PPF.

References	Properties	Comments
[48]	(0.15%, 0.30%, and 0.45%). PPF (12 mm) length and (0.25%, 0.50%, 0.75% and 1.0%) steel fiber (60mm) length in high-strength concrete (with 10% silica fume).	The study showed that mixed fibers of nominal proportions (0.85% steel fiber and 0.15% PP fiber) gave the highest resistance among other ratios, and the inclusion of concrete with PPF has increased porosity of concrete mixes, leading to a slight decrease in resistance to electricity while the decrease was greater for steel fiber. The use of both types of fibers with silica fume has reduced water absorption compared to non-silica fume mixes, and the concrete with a combination of 0.3% PPF and 0.7% steel fiber was less water-absorption.
[49]	PPF and macro-polymeric (MPF) in concrete with silica fume and nano-silica, the proportions of (MPF) were (0.25%, 0.5%, 0.75% and 1.25%) while PPF (0.1%, 0.2%, 0.3%, 0.4% and 0.5%) by volume fractions with different ratios of silica fume and nano-silica.	A reduction in workability was noticed when using PPF while the influence was lesser for the (MPF). The compressive strength improvement for 0.25% (MPF) and 0.1% (PPF) were 8% and 11.5% respectively up to 0.3% of PPF. The modulus of elasticity and the tensile strength increased. The optimum combination ratio of this study that gave an 18% enhancement in split tensile strength was (0.1% PPF and 0.9% MPF). The incorporation of optimum proportions of (fibers and pozzolans) caused an enhancement of physco-mechanical characteristics compared with the plain concrete and concrete of optimum incorporations individually.
[50]	Fibrillated PPF of (19 mm) length and hooked end deformed steel fiber of (60 mm) length at different ratios in high strength concrete beam (C60). A combination of both fibers or single use of each one was conducted.	The maximum structural stiffness was increased by 32% for (75%-25%) of (steel fiber-PPF), and preferable flexural qualification was mentioned for the same fiber proportions. Single-use of PPF has no effective action for delaying cracks of origination tension and concrete tensile strength amelioration.
[51]	PPF of (12 mm) length and crimped steel fiber of (25 mm) length in (M25) grade of concrete, with a hybridization ratio (0%, 0.5%, 1% and 1.5%) (50% each type).	The optimum hybrid ratio was (1.5%) i.e. (0.75% PPF and 0.75% steel fiber) that gave a 33.79% increase in compressive strength, 46.12% in tensile strength and 33.33% in flexural strength. The impact strength increased with hybrid ratio increment and for the sorptivity, 0.5% gave the same value of the control mix.
[52]	Mixed PPF of (12 mm length) and nylon fiber of (19 mm length) with varying volume ratios of (0.5%, 0.75%, 1%, 1.25% and 1.5%) into (M30) grade concrete containing 25% of recycled aggregate.	The compaction factor test and slump results decreased by fiber proportions increment. The compressive strength increased by up to 1% and then decreased. Accordingly, the highest results were obtained when adding 25% of PPF and 75% of nylon fiber.

[53]	Steel/polypropylene concrete by the addition of (1.0%-2.0%) steel fiber with (30, 60 and 80) aspect ratios and (0.1%, 0.15% and 0.2%) PPF of 167 aspect ratio.	The damage growth and stress-strain demeanor of the peak (strain and strength), post-peak ductility and toughness of the hybrid fiber concrete under tension and compression are promoted; stiffness regression and damage accumulation are attenuated via volume increase of PPF and steel fiber. Also, for responses prediction of hybrid fibers concrete materials and members that yielded to seismic loads and shear are modeled by the Abacus program.
[54]	(0.5%, 1%, 1.5% and 2%) of sisal fiber of (30 mm) length with PPF (0.4%, 0.8%, and 1.2%) of (12 mm) length into (M40) grade concrete.	(1.5%) sisal fiber was the optimum proportion for compressive and flexural strength with 7.19% and 8.185% increments. Further, the ratio (1.5% sisal fiber + 0.4% PPF) was the optimum hybrid ratio that gave 8.24%, 11.69% enhancement in compressive strength and flexural strength.
[55]	(steel fiber and / or PPF) with 0.25% - 1% amount in concrete type (ultra-high performance) the coarse aggregate type granite or granodiorite of about 2/8 mm grain size were utilized.	The use of 1% steel fiber ameliorated the compressive strength by 2.6% only while for 1% PPF it was minimized by 37%. The incorporation of 1% (0.5% PPF + 0.5% steel fiber) enhanced the compressive strength by 3.4%. The study declared a reduction in fracture energy with an increase of more fiber dosages and the microstructure was notably changed by increasing fiber amount.

The incorporation of fiber into conventional concrete will convert its brittle behavior to ductile. However, either ductility or strength can be enhanced by the addition of one type only, i.e. carbon or steel fiber have (high strength and terminal modulus) that significantly upgrade concrete strength while no enhancement is related to the (ductility) [56]. Also, crack resistance, ductility and corrosion renitence can be achieved in concrete using PPF that has low strength [57, 58]. A comparative study was made by using (Polypropylene fibers of 12 mm length, glass fiber of 15 mm length and steel fiber of 35 mm) in volumetric proportions of (0.125%, 0.125%, and 0.5%) respectively and concluded that the value of compressive strength for PPF concrete samples has decreased, as have been observed, while the flexural strength and water penetration depth has improved compared to reference samples, and the highest rate of resistance to electricity is recorded for the PPF concrete compared to other fiber concrete where the increments were 61.9% at 28 days. A big difference was not observed in concrete samples containing PPF and not reinforced concrete samples when the oxygen gas permeability coefficient is concerned [59]. Fig. 13 shows the test results of the study.



(a) (b) (c)

Fig. 13. a) Flexural strength b) Electrical resistivity and c) Water absorption of samples [59].

Utilizing concrete having two types or more of fibers (hybrid fiber) is accounted as a portentous solution for further strength and durability characteristics [57, 60]. The mechanical properties of (steel-PP) fiber were increased by (6.4%, 11.4%, 3.7%) for compressive, flexural and splitting tensile strength compared with the plain concrete, and for hybrid concrete of (basalt-PP) fiber, the increment does not have a big difference, while for (polyvinyl alcohol-PP) fiber concrete a reduction was recorded for splitting tensile and flexural strengths. Fig. 14-a shows each fiber content, and Figs. (14-(b, c and d)) show a comparison of test parameters between the three types of fibers [61].

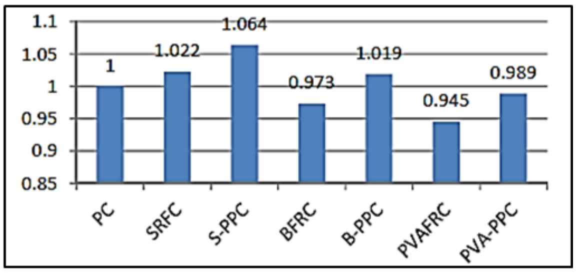
Thakur and Sood [54] used sisal fiber and PPF by weight of cement and observed a decrement in slump value by increasing fiber proportions Table 6 and an increment in compressive strength at 28 days of concrete containing (0.4% PPF+1.5% sisal fiber) by 8.24% Table 7, while the flexural increment was by 11.69% at the same proportions as presented in Table 8.

For hybrid fiber concrete of (PPF and basalt fiber), the carbonation renitence was most critically converted by (10%-20%) fly ash proportions incorporation as mentioned by [63], and at the same proportions, the concrete depth carbonization was modified by 41.7%-62.3% via carbonation time increment [62]. Wang et al. [62] recorded 14.1%, 22.8% and 48.6% increment for compressive, flexural and splitting tensile strength for (0.15% basalt-0.033% PPF) the mix which gives best synergy impact in high-performance concrete, however, the increment was not worthy via using one single doped of them. Fig. 15 shows basalt fiber and polypropylene fiber used in this study [63].

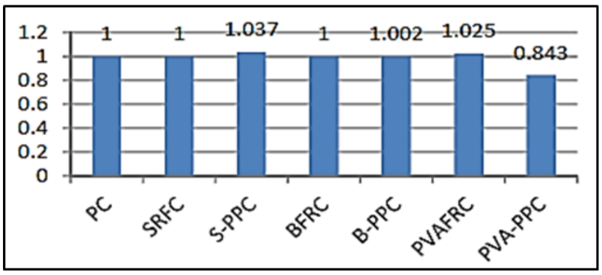
The mix workability/ rheological characteristics of concrete were found accounted on fiber geometry, types, and synergic characteristics between the fibers in the hybrid system.

	Steel fiber	Basalt fiber	Alcohol fiber	Polypropylene fiber
PC	0	0	0	0
SFRC	78	0	0	0
S-PPC	78	0	0	0.91
BFRC	0	5.3	0	0
B-PPC	0	5.3	0	0.91
PVAFRC	0	0	1.3	0
PVA-PPC	0	0	1.3	0.91

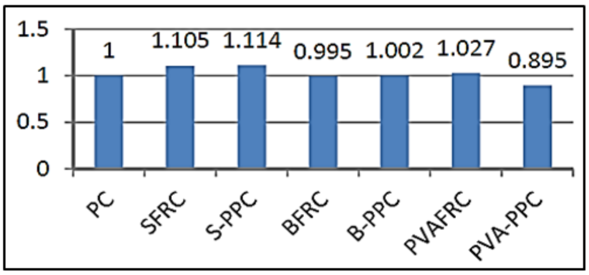
a) Fibers proportions.



b) Compressive strength of different concretes.



c) Tensile strength of different concretes.



d) Flexural strength of different concretes.

Fig. 14. Fiber proportions and values of mechanical strength of different concrete [61].

Table 6. Slump values of hybrid fiber concrete mixes [54].

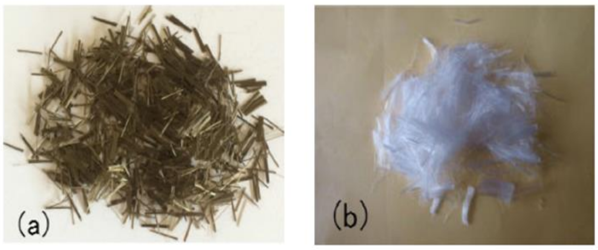
Mix Group	Hybrid fiber percentage (%) Sisal fiber	Polypropylene fiber	Slump (mm)
C	0	0	75
$HN_{1.9}$	1.5	0.4	60
$HN_{2.3}$	1.5	0.8	51
$HN_{2.7}$	1.5	1.2	0

Table 7. Compressive strength values of hybrid fiber concrete mixes [54].

Mix Group	Hybrid fiber percentage (%)	Compressive Strength (N/mm^2) 7 days	28 days
N	0	32.88	49.33
$HN_{0.4}$	1.9	40.44	54.22
$HN_{0.8}$	2.3	37.33	51.11
$HN_{1.2}$	2.7	33.44	49.66

Table 8. Flexural strength values of hybrid fiber concrete mixes [54].

Mix Group	Hybrid fiber percentage (%)	Flexural Strength (N/mm^2) 7 days	28 days
N	0	5.56	6.84
$HN_{0.4}$	1.9	6.52	7.64
$HN_{0.8}$	2.3	6.04	6.92
$HN_{1.2}$	2.7	5.68	6.88



Fig, 15. a) Basalt Fiber b) Polypropylene Fiber [63].

The manifestation of cracks was accorded in different sizes and several lengths; therefore, one of the best ways that manage this issue is by utilizing variant fibers with several lengths. Hence the gainful interaction of the hybrid system causes better performance when compared with the use of single fiber**.**

3. CONCLUSIONS

- The addition of high PPF volume fractions causes low workability due to uppermost shear renitence to flow.
- The PPF use in concrete leads to mechanical strengths increment till a proper (optimum) amount and decreases with further inclusion due to the impact of fiber balling and confusion inside the mix.
- The influence of PPF incorporation on tensile and flexural strength is more pronounced compared with compressive strength and elastic modulus.
- The addition of silica fume to PPF concrete has more effect when compared with non-fibrous concrete since its role of enhancing the transition zone also crack commencement elimination leading to ductile failure.
- PPF low volume fractions usage holds concrete micro-cracks composing and hence microstructure refinement.
- PPF concrete has ameliorative impact renitence and a little increase in freeze-thaw renitence when contrast with non-fibrous concrete.
- The use of PPF supplied a safer working ambiance, no corrosion risk and has good abrasion renitence.
- Concrete shrinkage of early age and concrete moisture loss can be reduced by even low fractions usage of PPF fiber.
- RA concrete workability is lower than that of NA concrete due to adhered mortar porosity and the workability gains a further reduction by more inclusion of PPF due to frictional renitence increment through PPF and concrete components.
- RA mechanical characteristics can be ameliorated via PPF incorporation; also the characteristics of porosity and water absorption can be reduced significantly.
- PPF concrete electrical resistivity is the highest compared with glass or steel fibers concrete but the gas permeability and impact renitence are the highest with steel fiber concrete.
- For hybrid concrete, PPF enhances toughness due to its durability characteristics also, it enhances the strain in the post cracking region due to its ductile and flexible properties.
- Fiber with a large size is helpful in macro cracks detention, while fiber with small size like PPF is helpful in micro cracks detention. Hence both macro and micro cracks vastness were controlled by utilizing hybrid fiber system.
- PPF concrete satisfies traditional concrete issues. It will therefore be a good alternative to address the current order for the construction industry.

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