The Effects of Polypropylene Fibers Additions on Compressive and Tensile Strengths of Concrete

Omar Asad Ahmad
Department of Civil Engineering, Faculty of Engineering Technology, Zarqa University, 132222, Zarqa, 13132, Jordan.

Mohammed Awwad
Department of Civil Engineering, Faculty of Engineering Technology, Al-Balqa Applied University

Corresponding Author Email: oahmad@zu.edu.jo

ABSTRACT

Concrete is one of the essential elements that used in different types of construction this days, but it has many problems when interacts with environmental elements such as water, air, temperature, dust and humidity. Also concrete made with Portland cement has certain characteristics: it is relatively strong in compression but weak in tension and tends to be brittle. These disadvantages make concrete limited to use in certain conditions. The most common problems appears on concrete are manifested by tearing, cracking, corrosion and spalling, which will lead to do some defect in concrete then in the whole construction, The fundamental objective of this research was to provide information about the hardened properties of concrete achieved by using easily available local raw materials in Jordan to support the practical work with partners in assessing the practicability of the mixes with polypropylene, and to facilitate the introduction of polypropylene fiber concrete (PFC) technology into general construction practice. Investigate the effect of the polypropylene fibers in PCC mixtures and on materials properties such as compressive strength, and tensile strength.

Also to investigate the use of polypropylene fibers in plain cubes and cylindrical concrete to improve it's compressive and tensile strengths to reduce early cracking and inhibit later crack growth. Increasing the hardness of concrete in this research is the main purpose to measure the deference of compressive strength and tensile strength between plain concrete and concrete mixture with polypropylene fibers different additions and to investigate its effect on reducing the early and later cracking problem. To achieve the goals of research 225 concrete test sample were prepared to measure it's compressive strength and tensile strength, the concrete test sample were three classes (A,B,C), sub-classified to standard , and polypropylene fibers added by the volume of concrete (5%, 10%, 15% and 20%).

The investigation of polypropylene fibers mixture with concrete shows that the strengths of the cement are increased and the cracking decreased. The results show that for class A the recommended addition were 5% of polypropylene fibers additions for compressive strength and 10% for tensile strength revels the best compressive strength that reach 26.67 Mpa and tensile strength that reach 2.548 Mpa records. Achieved results show that for classes B and C were the recommend additions 10% polypropylene fibers revels the best compressive strength records where they reach 21.11 and 33.78 Mpa, records reach for tensile strength 2.707 and 2.65 Mpa respectively.

Keywords-Polypropylene, Effects, Compressive, Tensile, strengths, Concrete, Construction.

1. INTRODUCTION

Since the concrete is the oldest manmade building materials used by Romans as early as 509 B.C, concrete has become one of the most commonly used building material. Concrete used as building materials is a composite material made from several readily available constituents (aggregates, sand, cement, water). It is a versatile material that can easily be mixed to meet a variety of special needs and formed to virtually any shape. Concrete mainly consists of cement, fine aggregates, coarse aggregates and water which mixed together. Admixtures added sometimes to change some of concrete properties. It is a widely used construction material because of its ease of construction, low cost of its ingredients and its good durability [1].

The properties of concrete can be classified as fresh or hardened. The Properties of fresh concrete was controlled by workability, consistency, and segregation and bleeding. The strict definition of workability is the amount of useful internal work necessary to produce full compaction. Consistency is the fluidity or degree of wetness of concrete and its generally dependent on the shear resistance of the mass it also a major factor in indicating the workability of freshly mixed concrete. Segregation refers to a separation of the components of fresh concrete, resulting in a non-uniform mixture. The primary causes of segregation are differences in specific gravity and size of constituents of concrete. Moreover, improper mixing, placing and consolidation also lead to segregation. Bleeding is the tendency of water to rise to the surface of freshly placed concrete. It caused by the inability of solid constituents of the mixture to hold all of mixing water as they settle down. Testing of fresh concrete was only slump test. The major way to describe the properties of hardened concrete is compressive and tensile strength. Strength usually gives an overall picture of the quality of concrete because it is related to the structure of cement paste [2]. There are some factors affecting strength such as water/cement ratio, curing time, cement and aggregate. Since the W/C ratio controls the porosity of concrete, it controls the strength as well. Therefore, in practice, we can assure the strength of properly compacted concrete at a given age by specifying the W/C ratio. It is usually wise to use as low water content as possible, since higher water added to concrete mixture higher the porosity regardless the fact that the w/c ratio is being kept constant. The ratio between the strengths at curing times depends on cement type, and curing temperature. This would help to anticipate whether our mixture strength will achieve the required strength or not.

The effect of Portland cement on concrete strength depends on the chemical composition and fineness of the cement. Cement Chemical composition like C3S and C2S controls early and later strength, respectively. Aggregates Shape and Texture controls the bond between aggregate and cement and contribute to the stress level at which micro-cracking begins. Therefore, crushed aggregate could lead to higher concrete strength than gravel [2].

Fiber Reinforced concrete (FRC) is Portland cement concrete reinforced with more or less randomly distributed fibers. In FRC, thousands of small fibers are dispersed and distributed randomly in the concrete during mixing, and thus improve concrete properties in all directions. Fibers help to improve ductility performance, pre-crack tensile strength, and compressive strength. Several different types of fibers have been used to reinforce the cement-based matrices. The choice of fibers varies from synthetic organic materials such as polypropylene or carbon, synthetic inorganic such as steel or glass, natural organic such as cellulose or sisal to natural inorganic asbestos. Currently the commercial products are reinforced with steel, glass, polyester and polypropylene fibers. The selection of the type of fibers is guided by the properties of the fibers such as diameter, specific gravity, young's modulus, tensile strength etc and the extent these fibers affect the properties of the cement matrix[3].

Polypropylene (PP) is a synthetic resin built up by the polymerization of propylene. PP is a gaseous compound obtained by the thermal cracking of ethane, propane, butane, and the naphtha fraction of petroleum [4] (Fig.1). In other research, Polypropylene is a versatile thermoplastic material, which is produced by polymerizing monomer units of polypropylene molecules into very long polymer molecules or chains in the presence of a catalyst under carefully, controlled heat and pressure. Propylene is an unsaturated hydrocarbon, containing only carbon and hydrogen atoms: [3]

Today is very common to add polypropylene fiber into concrete for strengthening concrete and for protection of concrete against micro cracks. PP fibers used in concrete to obtain a much better, more stable surface and more resistant piece of concrete. This increases the lifetime of this piece of concrete-especially true where this is exposed to change weather conditions. The length of fiber should always be as short as possible in order not to damage the fibers [3].

Figure 1 Polypropylene fibers

The past studies indicated that the addition of PP resulting a reduction in bleeding, therefore a reduction in bleeding improves the surface integrity of concrete, reduces the probability of cracks and increase the compressive strength [5]. Permeability, cracking and corrosion were found to be interrelated and the effects of these factors affect the degree of permeability, which in turn affects durability. Low permeability is the key to good durability. Concrete tends to be classified in terms of durability by reference to the compressive strength, thus giving an indication of density and therefore alluding to low porosity and subsequent durability [6].

The objective of this research was to provide information about the hardened properties of concrete achieved by using easily available local raw materials in Jordan to support the practical work with partners in assessing the practicability of the mixes with polypropylene, and to facilitate the introduction of polypropylene fiber concrete (PFC) technology into general construction practice, and investigate the effect of the polypropylene fibers in PCC mixtures and on materials properties such as compressive strength, and tensile strength. Also to investigate the use of polypropylene fibers in plain cubes and cylindrical concrete to improve it's compressive and tensile strengths to reduce early cracking and inhibit later crack growth.

2. MATERIALS AND METHODS

Local Aggregate was used in this project from Almnaseer Company (Jordan). Aggregates typically constitute 75% of concrete volume. Hence, aggregate types and sizes play an essential role in modifying the concrete properties as noted in the previous section [2].Grain size distribution according to ASTM C 136-01a standard test method for Sieve analysis of fine and coarse aggregates [7]. The results of testing material and properties showed in tables 1,2,3,4,5.

Table 1: Graduation of used aggregates

	Sieve size (mm)										
	37.30	25.40	19.00	9.53	4.75	2.36	1.18	0.60	0.30	0.15	0.075
coarse	100	100	62.1	1	0.9	0.8	0.8	0.8	0.7	0.7	0.5
medium	100	100	100	35.2	3.3	3	2.7	2.2	1.6	1.1	0.8
Sand	100	100	100	100	98.4	97.5	90.5	71.2	13.5	4.1	2.7

Table 2 Results of Bulk and Apparent specific gravity of used materials.

Test specifications	coarse aggregate	medium aggregate	Fine aggregate (sand)
Weight of dry sample (**Wd**)	966.5	1131	290.2
Weight of standard surface dry sample **Wssd**)	984	1145	295
Weight of submerged sample (**Wsub**)	619.3	717.2	
Dry volume (**Vd**)	347.2	413.8	117.1
Volume of standard surface dry sample'(**Vssd**)	364.5	427.8	121.9
Apparent specific Gravity (**Gapp**)	2.78	2.73	2.48
Bulk specific gravity (**Gbulk**)	2.65	2.64	2.38
Water absorption (**Abs**)	1.81%	1.24%	1.65%

Table 3: Determination of Aggregate Impact Value (AIV) of used materials.

	first sample	Second sample
Weight of empty can (W1)	615.4	615.4
Weight of can + sample (W2)	916	907.2
sample weight (W3)	300.6	291.8
Weight of sample retained on sieve (2.36mm). (M1)	264.7	246.5
Weight of sample passing from sieve (2.36mm) (M2)	35.9	45.3
Impact value (I.V.)	11.94	15.52
Los Angeles test: Percent of Abrasion (Abr. %)	25.16	

Table 4: Determination of Fineness of Cement

	Weight (g)
Sample weight	500
Empty sieve weight	*582*
Sieve + retained weight	*594.6*
Retained weight	*12.6*

Table 5: component weights for 1m3 of concrete classes

Types of materials (kg/m^3)	**Class A**	**Class B**	**Class C**
Weight Coarse	356	593	741
Weight Medium	593	593	444
Weight Silica sand	593	593	593
Weight Cement	296	296	370
Water content (lit/m^3)			
Water	222	252	222
W/C	0.75	0.85	0.60
Slump test (without PP)	6	11	5

3. RESULTS AND DISCUSSIONS

The properties of hardened concrete can be significantly improved by fibers. As we said before the strength of concrete is the major way to describe the properties of hardened concrete as compressive and tensile strength. Strength usually gives an overall picture of the quality of concrete because it is related to the structure of cement paste [2]. In our study we measure the strength of concrete by compressive and tensile strength tests. From each concrete mixture, total of 225 specimens, 45 specimens of them were cast in cylindrical moulds of 150 mm diameter and 300 mm height. And 180 of them were cast in cubes of 150 mm cubes. The cubes were used for compressive strength test, while the cylinders were used for splitting tensile strength test. According to Bs1881: part 116:1983[15] Method of determination of compressive strength of concrete cubes. List of tables and figures represents compressive strength results of the concretes in class A, B and C mixes. All classes' compressive strength results are shown in Table 7, (Fig. 2-5).

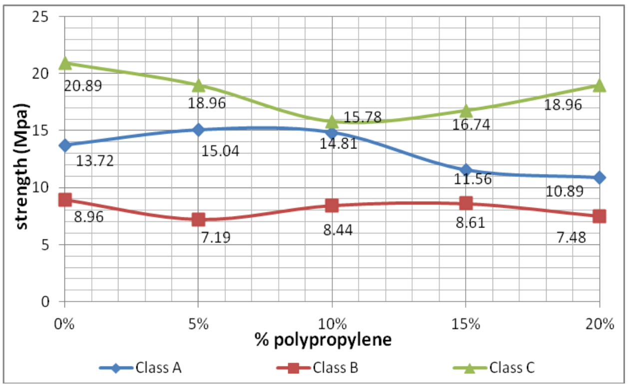

Figure 2: Results of compressive strength on all class after 3 days.

Table 7: Compressive strength of mix classes

Age (days)	Cube strength at polypropylene percent of (Mpa) Class A				
	0 %	*5%*	*10 %*	*15 %*	*20 %*
3	13.7	**15.0**	14.8	11.6	11.0
7	16.6	**18.4**	17.6	13.1	13.6
14	22.0	**22.9**	20.8	17.5	16.4
28	25.9	**26.7**	22.7	22.3	19.9
	Cube strength at polypropylene percent of (Mpa) Class B				
3	**8.97**	7.19	8.44	8.61	7.48
7	**13.04**	9.04	12.4	11.6	12.1
14	**16.22**	11.2	16.5	14.7	11.8
28	17.41	13.6	**21.1**	16.3	14.7
	Cube strength at polypropylene percent of (Mpa) Class C				
3	**20.89**	19.0	15.8	16.7	19.0
7	21.63	21.1	21.8	**23.3**	21.3
14	24.67	27.6	**28.3**	23.9	23.6
28	31.11	30.5	**33.8**	27.3	28.5

The addition of polypropylene fibers at low values i.e. 5% actually increases the 28 days compressive strength by about (2.85%) but when the volumes get higher like 15% to 20% then the compressive strength decreases. The results in table 3.1 seem to indicate that there may be an effective volume threshold for adversely affecting the compressive strength of concrete that is exceeded at 5%. In class B, the addition of polypropylene fibers at 0.1 % increases the 28 days compressive strength by about (21.25%) the compressive strength decreases when the volumes get higher like 0.15% to 0.20% then. Table 3.3 indicates that the class C increases the 28 days compressive strength by about (8.58%) in the addition of polypropylene fibers at 0.1%, but when the volumes get higher like 0.15% to 0.20% then the compressive strength decreases. All things considered, it appears that at low dosage rates (0.05 and 0.10 the addition of polypropylene fibers) does not significantly detract from, and even improve the compressive strength. Higher dosage rates however decrease the strength of concrete matrix due to higher volumes of fibers interfering with the cohesiveness of the concrete matrix [28]. The graphical representation of the tests results is given in Figures 3.2, 3.3 and 3.4.

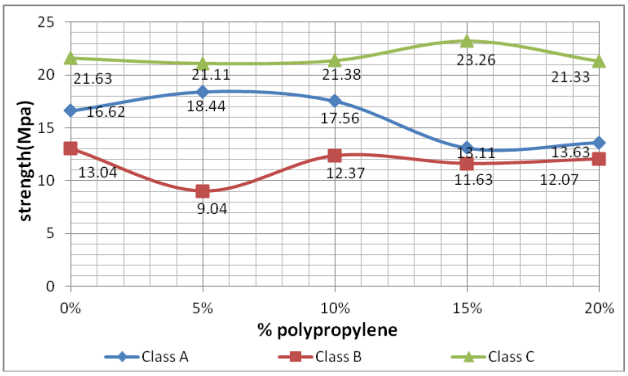

Figure 3: Result of compressive Strength on all classes after 7 days.

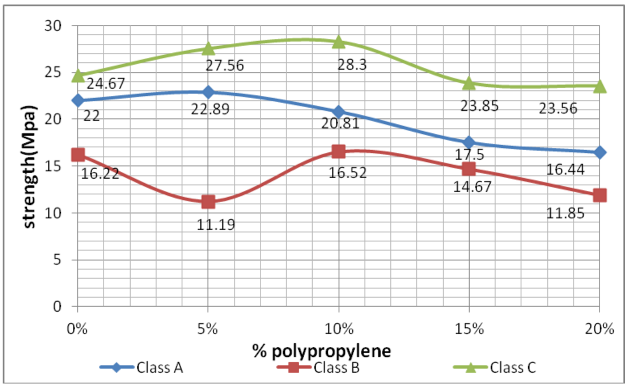

Figure 4: Result of compressive Strength on all classes after 14 day.

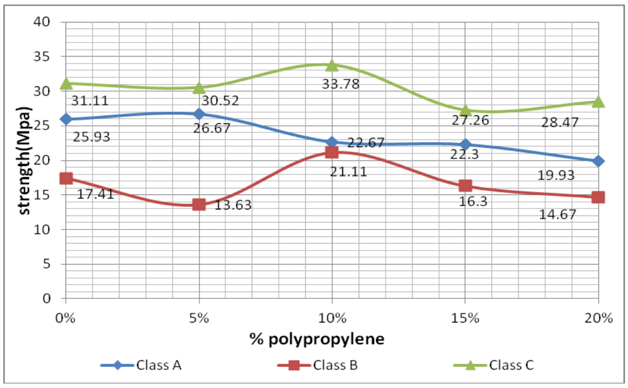

Figure 5: Result of compressive Strength on classes after 28 day.

According to ASTM C 496 – 96, standard test method for splitting tensile strength of cylindrical concrete specimens [16]. Table 8 and figure 6 showing splitting tensile strength results of the concretes in class A, B and C mixes.

Table 8: Splitting tensile strength.

Age (days)	Cylinder strength at polypropylene percent of (Mpa) Class A				
	0 %	*5%*	*10 %*	*15 %*	*20 %*
28	2.495	2.282	**2.548**	2.176	2.176
	Cylinder strength at polypropylene percent of (Mpa) Class B				
28	1.699	1.699	**2.707**	2.442	1.858
	Cylinder strength at polypropylene percent of (Mpa) Class C				
28	**3.45**	2.23	2.65	3.34	2.81

According to tables 3.4 and 3.5, splitting tensile strength of concrete it show that in class A and class B increases only with addition of fibers up to about 0.10% after which the tensile strength decreases with addition of more fibers. Fibers must be uniformly distributed in mix and fiber proportion must be carefully selected. The tensile strength increases about (2.12 % ~ 59.3%) up to 0.10% after which it decreases. Tensile strength is increased due to bridging mechanism of polypropylene fibers and after certain ration it reduced the bond strength between concrete ingredients so results in quick failure as compared to less volumes of fibers. The graphical representation of the test results is given in Figures 3.9 to 3.10 [28]. Table 3.6 indicates that when added polypropylene to the class C concrete doesn't effect at tensile strength since the maximum value was at 0% polypropylene. Also, we discuss splitting tensile test of three classes in 28 days in the following chart. Figure 3.12 shows the result of three classes.

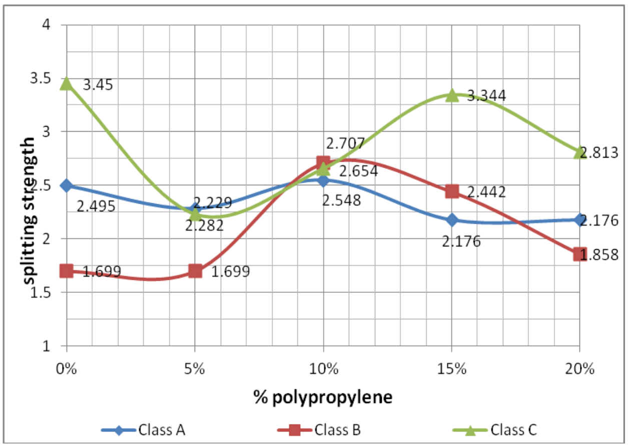

Figure 6: Result of splitting tensile Strength on all classes after 28 days.

The cost considered as one of the most important part of any project which plays an important role ensuring the economic success of the project as shown in Tab.9. So, we're going to demonstrate a Cost-Benefit Analysis of polypropylene additions to the concrete, and whether we will get any benefit from polypropylene or not. This study includes pricing concrete and pp and changing in the physical properties of concrete after different additions of pp. Concrete price classified depending on the compressive strength, the higher the strength the higher the price and it changes from a day to another, nowadays concrete price of one cubic meter for strength of 20, 25 and 30 MPa are 77, 80 and 82.5 US $ respectively. Polypropylene is priced in accordance with weight, one kilograms of PP is about 1.42 US $. Quantity of PP added to the concrete increasing the price of concrete according for its price. We will focus on the optimum pp percentage for each class.

Table 9: Show the cost of PP additions to concrete

Class (MPa)	Optimum pp%	Weight (Kg) for 1m³	Price of pp (US $)	Price of concrete + PP (US$/1m³)
A (25)	5	1.48	2.12	57. 48
B (20)	10	2.96	4.21	56. 96
C (30)	10	2.96	4.21	60. 96

Polypropylene is hydrophobic, meaning it does not absorb water. Polypropylene fibers are not expected to bond chemically in a concrete mix, but bonding has been shown to occur by mechanical interaction [17].The incorporation of discrete and discontinuous fibers of PP into a cement brittle matrix serves to increase the compressive strength, fracture toughness of the concrete by the result of the crack arresting process and increase of the flexural and tensile strengths. In 1965, Shell Chemical Co. started investigations on Polypropylene to be used in concrete [18]. Polypropylene fibers are stronger as a result of more developed plastic materials, which offered a potentially low priced polymer.

The results of Dardare [19] indicate that incorporation of polypropylene fiber in concrete can increase compressive strength. The increase is dependent on the volume fraction and the length of the fiber. The results on our research were good, which increased the compressive strength in average of 11 % as shown in table 4.2.

Table 10: Percentage increasing of compressive strength of concrete

Class	Compressive strength without PP	Compressive strength with PP	Increasing %	Average increasing %
A	25.93	26.67	2.85	10.89 %
B	17.41	21.11	21.25	
C	31.11	33.78	8.58	

Concrete is very brittle under tensile stresses and impact loads. The cause of concrete cracks is due to the inherent tensile weakness of the material. Plain concrete has a low tensile strength and a low strain capacity at fracture. Fibers bridge across the concrete matrix Figure 4.1 helping to control shrinkage cracking during the plastic stage and matrix micro cracks that occur as the concrete is loaded. This helps to add post-cracking ductility to concrete. Fibers can prevent the occurrence of large crack widths that are either unsightly or permit water contaminants to enter, causing corrosion of reinforcing steel or potential deterioration of concrete [20]. In addition to crack control and serviceability benefits, use of fibers at high volume percentages can substantially increase the matrix tensile strength [21].

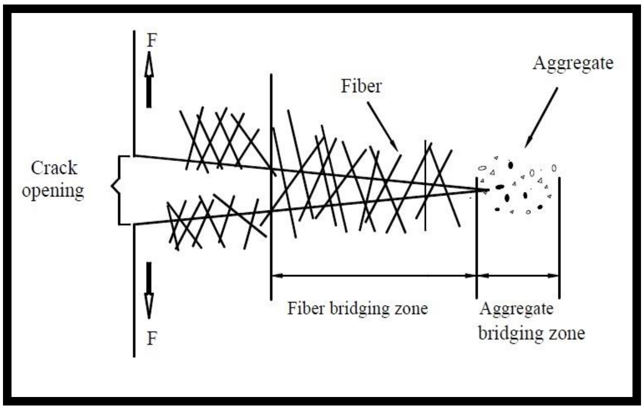

Figure 7: Fiber bridging across a concrete crack [22]

Figure 4.2 shows the stress-strain curves for concrete with continuous PP fiber, discontinuous PP fibers and without PP fibers matrix material [23]. Curve 2 for discontinuous random fibers has three regions: an initial steep region and a second region, where the stress drops sharply as it is transferred to PP fibers bridging cracks; and another region, where the stress levels off and the fibers generally pull-out rather than break. Figure 4.3 shows the stress-strain/deformation curves for concrete with and without PP [24]. It's also having a significant effect in increasing the range of deflection for concrete as shown in figure 4.4.

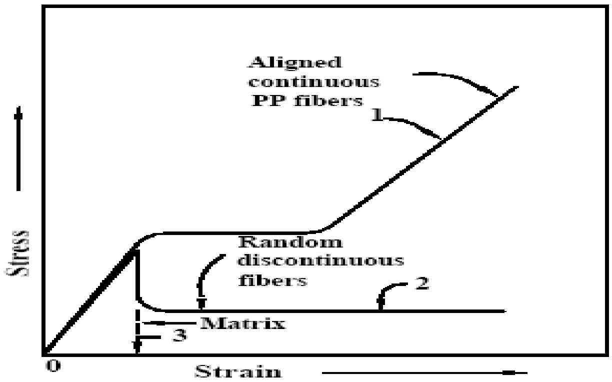

Figure 8: Stress-strain curves for cement composites containing PP fibers [23]

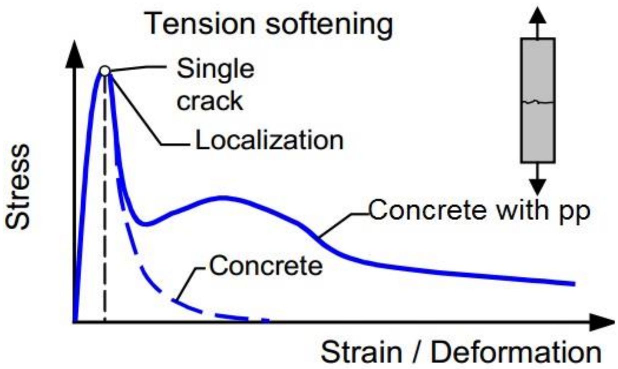

Figure 9: Stress-strain/deformation for concrete with and without PP [24].

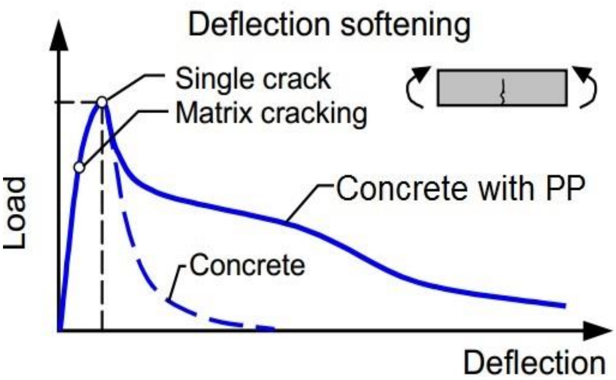

Figure 10: Changing in deflection range for plain concrete and concrete with PP [24].

As important as the capacity of a structure to resist the loads applied on it, is to get durable structures in time capable of resisting weathering action, chemical attack, abrasion and other degradation processes during their service life with the minimal maintenance. Cracks play an important role as they change concrete structures into permeable elements and consequently with a high risk of corrosion. Cracks not only reduce the quality of concrete and make it aesthetically unacceptable but also make structures out of service. If these cracks do not exceed a certain width, they are neither harmful to a structure nor to its serviceability. Therefore, it is important to reduce the crack width and this can be achieved by adding PP fibers to concrete as we showed above. Controlling cracks means, controlling shrinkage also, by reducing the damages happened because of shrinkage cracking, figure 4.5.

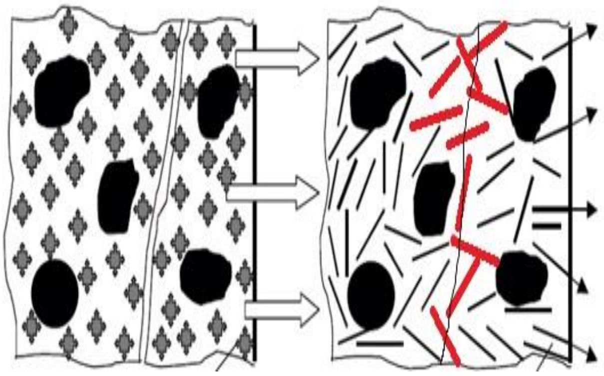

Figure 11: Reducing the damages of shrinkage cracking.

From our cost studies we can summarize the advantages of PP fibers additions to concrete:

Fibers enhance the compressive strength, flexural strength, shear strength, ductility, toughness and energy absorption capacity of concrete.

With fibers, the internal stresses are much more evenly distributed throughout the cross section of the structure and along the length of the in-place concrete.

Fibers prevent micro cracks, and thus protect the porous concrete from further aggressive environmental attack. Large visible cracks may occur with concrete. Even if a fiber added structure cracks sometimes, but the cracks are micro in size, or small enough to make them invisible and acceptable in width [25].

Fibers reduce the increase in permeability due to cracking in concrete [26].

The starting time of micro cracking in concrete is delayed with the addition of fiber.[27]

Fibers are most effective in contributing to the post-cracking resistance of cementations composites by bridging the cracks and providing restraint to their opening [22].

Increasing durability by preventing the environmental attacks.

Reducing the maintenance cost by reducing damages of crack and shrinkage.

4. CONCLUSION

From this study following conclusions have been drawn: Polypropylene fiber concrete (PFC) is a high strength mixture of aggregates, cement, and water.

PP is used to manufacture high strength sectioned.

The length of fibers always to be as short as possible in order not to damage the fibers.

After cost studies we improved that adding PP fiber to concrete improves its properties very much and it's absolutely not costly comparison with the benefits we gain.

Normal concrete compressive strengths for class A, B and C are 25.93, 17.41 and 31.11 Mpa respectively.

A polypropylene fiber increases the compressive strength in class A cubes at 3, 7, 14 and 28 days respectively by 9.6%, 10.95%, 4.05% and 2.85%. These percents of increases are done by adding 5% by volume of concrete. While in the splitting tensile strength the increasing was 2.12% when we added 10% of polypropylene.

In the class B polypropylene fiber increases the compressive strength at 14 and 28 days by 1.85% and 21.25 respectively when added 10%. Likewise, by adding 10% of polypropylene the splitting tensile strength increases by 59.3% at 28 days.

A polypropylene fiber increases the compressive strength in class C at 14 and 28 days by 14.4% and 8.58% respectively by adding 10%. Also in the splitting tensile there is no increasing.

From previous tests shows that the best mixing ratios of concrete with polypropylene to reaching maximum strengths is to add PP with 5% for class A to 10% for class B and C. For tensile strength the best percent of adding PP is also 10% for class A and B. On the class C the tensile strength was failed.

Increasing dosages of PP fibers in concrete effect adversely on the strength of specimens due to higher volumes of fibers interfering with the cohesiveness of the concrete matrix.

Fibers must be uniformly distributed in mix and fiber proportion must be carefully selected.

REFERENCES

[1] The Roman Pantheon: The Triumph of Concrete. Romanconcrete.com. Retrieved on 2013-02-19.

[2] A.M. Neville & J.J. Brooks, "concrete technology" (2004).

[3] FIBER REINFORCEMENT OF CONCRETE STRUCTURES R. Brown, A. Shukla and K.R. Natarajan University of Rhode Island.

[4] Richard G. Mansfield "Polypropylene in the Textile Industry", Plastics Engineering, June 1999, 30.

[5] "Experimental relationship between splitting tensile strength and compressive strength, "http://www.science direct.com April.21, 2003.

[6] The effect of polypropylene film on the durability of concrete (Material Specialty Conference of the Canadian Society for Civil Engineering (Montréal, Québec, Canada 5-8 juin 2002 / June 5-8, 2002)).

[7] ASTM C 136-01a, standard test method for "Sieve analysis of fine and coarse aggregates"

[8] ASTM standards: C 127-88, Standard test method for specific gravity and absorption of coarse aggregate.

[9] ASTM standards: C 131-96, Standard test method for resistance to degradation of small – size coarse aggregate

[10] ASTM C 136-01a, standard test method for "Sieve analysis of fine and coarse aggregates"

[11] According to ASTM C128-97, Standard Test Method for Specific Gravity and Absorption of Fine Aggregate

[12] According to ASTM C786 / C786M - 10 Standard Test Method for Fineness of Cement and Raw Materials by the 300-µm (No. 50), 150-µm (No. 100), and 75-µm (No. 200) Sieves.

[13] ASTM C511 standard.

[14] According to ASTM Designation: C 496 – 96 Test for slump of Portland cement concrete.

[15] According to Bs1881: part 116:1983 Method of determination of compressive strength of concrete cubes.

[16] According to ASTM C 496 – 96 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

[17] Rice, E., Vondran, G., and Kungbargi, H., (1988), "Bonding of Fibrillated Polypropylene Fibers to Cementitious Materials", Materials Research Society Proceedings, Pittsburgh, PA, Vol. 114, pp. 145-152.

[18] Zonsveld, J. J., (1975), "Properties and Testing of Concrete Containing Fibers Other Than Steel", RILEM Symposium on Fiber-Reinforced Cement Concrete, London, pp 217-226.

[19] Dardare,J.,(1975), "Contribution à l'etude du Comportement Mécanique des Bétons Renforcés avec des Fibres de Polypropyléne", RILEM Symposium on Fiber- Reinforced Cement and Concrete, London, ed. A.M. Neville, pp. 227-235.

[20] Naaman, A.E., March (1985),"Fiber Reinforcement for Concrete", Concrete International: Design and Construction, Vol. 7, pp. 21-25.

[21] Shah, S. P., Nov. (1991), "Do Fibers Increase the Tensile Strength of Cement Based Matrices?" ACI Materials Journal, Vol. 88, No. 6, pp. 595-602. 128

[22] Beaudoin, J.J., (1990), "Handbook of Fiber-Reinforced Concrete. Principles, Properties, Developments and Applications", Noyes Publications, Park Ridge, NJ, pp. 332.

[23] Rice, E., Vondran, G., and Kungbargi, H., (1988), "Bonding of Fibrillated Polypropylene Fibers to

Cementitious Materials", Materials Research Society Proceedings, Pittsburgh, PA, Vol. 114, pp. 145-152.

[24] Löfgren, I. "Fibre-reinforced Concrete for Industrial Construction-a fracture mechanics approach to material testing and structural analysis". PhD Thesis, Dep. of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg, 2005.

[25] Grzybowski, M, June (1989) ,"Determination of Crack Arresting Properties of Fiber Reinforced Cementitious Composites" ,Royal Institute of Technology, Stockholm, Sweden, Chapter 12.

[26] Rapoport, J., Aldea, C, Shah, S.P., Ankenman, B., and Karit, A.F., January, (2001), "Permeability of Cracked Steel Fiber-Reinforced Concrete" Technical Report No. 115, National Institute of Statistical Sciences (NISS), Research Triangle Park, NC.

[27] Grzybowski, M., and Shah, S. P., Mar.-Apr. (1990), "Shrinkage Cracking in Fiber Reinforced Concrete", ACI Materials Journal, Vol. 87, No. 2, pp. 138-148.

[28] A study on properties of polypropylene fibers research (university of Engineering and technology taxila, Pakistan).