The International Journal of Engineering and Science (IJES)
|| Volume || 6 || Issue || 10 || Pages || PP 16-25 || 2017 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Recycled Plastic Fibers for Minimizing Plastic Shrinkage Cracking of Cement Based Mortar

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ABSTRACT

The development of new construction materials using recycled plastic is important to both the construction and the plastic recycling industries. Manufacturing of fibers from industrial or postconsumer plastic waste is an attractive approach with such benefits as concrete performance enhancement, and reduced needs for land filling. The main objective of this study is to investigate the effect of Plastic fibers obtained locally from recycled waste on plastic shrinkage cracking of ordinary cement based mortar. Parameters investigated include: fiber length ranging from 20 to 50 mm, and fiber volume fraction ranging from 0% to 1.5% by volume. The test results showed significant improvement in crack arresting mechanism and substantial reduction in the surface area of cracks for the mortar reinforced with recycled plastic fibers compared to plain mortar. Furthermore, test results indicated that there was a slight decrease in compressive strength of mortar reinforced with different lengths and contents of recycled fibers compared to plain mortar. This study suggests that adding more than 1% of RP fibers to mortar, can be used effectively for controlling plastic shrinkage cracking of cement based mortar, and thus results in waste reduction and resources conservation.

Keywords: *mortar, plastic, shrinkage cracking, compressive strength, RF recycled fibers.*

Date of Submission: 13-10-2017 Date of Publication: 27-10-2017

I. INTRODUCTION

PLASTICSHRINKAGECRACKING is a primary cause of reduced performance in cement-based composites [1–3]. In particular, wide surfaces such as bridge slabs or paving and parking lot floors are affected by restraint, high rates of evaporation, and high temperatures during the initial placing of cement-based composites, which can cause plastic shrinkage cracking before the cement-based composite has hardened completely [4–7]. Cracking can also occur after casting and before hardening if the temperature of the cement-based composite differs from the outside temperature [6,7]. Plastic shrinkage occurs in all fresh cement-based materials within the first few hours after they have been placed [8], especially during hot, windy and dry weather which can cause a fast rate of surface water evaporation. When the rate of evaporation exceeds the rate of bleed water rising to the surface, the concrete mixture will begin to shrink [4]. If the shrinkage is restrained, tensile stress develops and can cause cracks.To prevent plastic shrinkage cracking, the most widely accepted method is the use of randomly distributed fibers in volume fractions below 0.5% [9]. The fibers provide bridging forces across cracks and thus prevent the cracks from growing. In addition, the large pores that are introduced at the fiber-matrix interfaces are believed to provide bleeding channels which supply water to replenish the water lost from the surface. As a results, the capillary stress between the solid particles, and hence the free plastic shrinkage potential, is reduced [10].

Polyethylene terephthalate (PET) is one of the most important and extensively used plastics in the world, especially for manufacturing beverage containers. The current worldwide production of PET exceeds 6.7 million tons/year and shows a dramatic increase in the Asian region due to recent increasing demands in China and India [11]. Polyethylene terephthalate (PET) is a plastic material commonly used in beverage containers and other products. However, PET can cause environmental damage if it is not disposed of properly, and research on the recycling of PET bottles has specified that the process can cause considerable environmental and economic problems [12].

Recycled fibers from various sources have been studied as reinforcement in concrete, including tire cords, carpet fibers, feather fibers, steel shavings, wood fibers from paper waste, and high density polyethylene [13]. Polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), polyvinyl chloride (PVC), nylon, aramid, and polyesters are commonly used as short plastic fibers in concrete members [16–18]. Alhozaimy and Alshannag [19] testresultsindicated a significant improvement in crack-arresting mechanism of the concretes reinforced with recycled plasticof low density polyethylene fibers (LDPE) compared to plain concrete. They observed that increasing therecycled fiber volume up to 3% caused no plastic shrinkage cracking of concrete slabs.

Constructing reinforcing fibers from waste PET bottles to control plastic shrinkage cracking in cement-based composites is an effective way to reuse the bottles. Because the bottles are plastic, they have many limitations and disadvantages. The characteristics and low surface energy of plastic materials result in a poor mechanical bond with the cement-based composite [15]. Low mechanical bond strengths may not provide sufficient bridging force to control crack development [21–23]. Poor mechanical bond strength may also cause internal micro-cracks in the interfacial mechanical bond area between a fiber and the cement matrix [22,23].

Recently there has been a growing interest in the use of recycled plastic fibers as secondary reinforcement in concrete because they are generally considered to be non-biodegradable and may not need to be purified and separated to the same extent as recycled plastic used in other applications [13,14]. Constructing reinforcing fibers from waste PET bottles to control plastic shrinkage cracking in cement-based composites is an effective way to reuse the bottles [15].

This study investigated the plastic shrinkage cracking of cement based mortar reinforced with recycled plastic RP fibers. Fibers were formed into two lengths and added to cement-based composite in four different fractions by volume.

II. EXPERIMENTAL PROGRAM

Ordinary Portland cement (Type I) was used. Red sand with specific gravity of 2.66 and the absorption capacitywas 0.38% was used as fine aggregates.

The recycled Plastic RP fibers were obtained from small workshops operating in Jeddah. Process of recycling plastic includes; first, placing the plastic waste in a machine to be cut into small pieces. Second, these small pieces of plastic will be melted at a temperature depending on the plastic type. Third, the melted plastic will pass through perforated plate and extracted as a plastic wire with the diameter of 0.5-2.0 mm size. Finally, the plastic wires were cut into small pieces to be in the form of fibers. For the present study, recycled PET fibers of 0.5-2.0 mm diameter will be cut into 20 mm and 50 mm long pieces and used as reinforcing fibers for mortar at volume fractions ranging from 0 to 1.5%. (Figures 1, 2) shows images of the manufactured recycled PET fibers, respectively. The basic properties of fibers are presented in Table I.

TABLE I: PROPERTIES OF RECYCLED PLASTIC FIBERS (RPF)

Strand shape	Dimension (mm)	Length (mm)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (MPa)
Flat	0.5 x 2.0	20	1.38	310	$1.02X10^4$
Flat	0.5 x 2.0	50	1.38	310	$1.02X10^4$

Plastic shrinkage cracking test plan and compressive strength tests were conducted for the various fiber lengths and fiber volume fractions. The mix proportion by weight of cement was 0.50:1.0:2.0 (water:cement: sand). Table IIpresents list of specimens and the number of specimens used for each combination of the cement-based composites used in the plastic shrinkage cracking tests. The mold used in the test was a 900 x 600 x 100 mm panel. The mortar was placed in the mold; after casting it was kept in a controlled environment at a temperature of 24 ± 2^{o}C, a humidity of 42 ± 3%, and wind speed of 6 m/s. It was monitored for 24 h, during which time visible cracks appeared. Compressive strength test was performed on cube specimen (100×100×100 mm) tested accordance with BS 1881: part 116 procedure [24].

TABLE II: LIST OF SPECIMENS AND THE NUMBER OF SPECIMENS USED FOR EACH COMBINATION.

Design Mix.	Fiber Length (mm)	Fiber Volume Fraction %	Number Specimen Plastic Shrinkage	Number Specimen Compressive Strength
N.F.1&2*	---	---	2	9
20L.F.3&4**	20	0.50	2	9
20L.F.5&6	20	1.00	2	9
20L.F.7&8	20	1.50	2	9
50L.F.9&10***	50	0.50	2	9
50L.F.11&12	50	1.00	2	9
50L.F.13&14	50	1.50	2	9

* : Specimen mortar not include RP fibers. ** : Specimen mortar include RP fibers of 20 mm length
*** : Specimen mortar include RP fibers of 50 mm length

Fig. 1: Picture of sample (20 mm) RPF

Fig. 2: Picture of sample (50 mm) RPF

For the slab panels placed inside the laboratory and exposed to wind, the blower was left operating overnight generating wind speed of 6.0 m/s. The blower was placed such that it covered the whole slab uniformly. The wind velocity was measured using a digital anemometer. Directing channel wasused to set the direction of air blower toward the slab panels after casting the mixture as shown in figure 3. The temperature of 24 ± 2^{o}C, a humidity of 42 ± 3%, and mortar temperature of 34 to 39^{o}C. It was monitored for 24 h, during which time visible cracks appeared. Trial mortar mixes were prepared in civil engineering concrete laboratory to monitor the plastic shrinkage cracking on the slabs, using a rotary planetary mixer with capacity of 180 liters.

Fig. 3: Shape of directing channel for blower

A. Test on Fresh Mortar

The flow of the mortar casting in this investigate measured using flow table test, the range value between (100-110%).

The water evaporation was expressed as percentage of water evaporated and the rate of evaporation. The percentage of water evaporated was calculated as the ratio of water evaporated to the total water added to the mix. The rate of water evaporation was evaluated by recording the change in weight using a digital balance of 0.01-g sensitivity. The evaporation rate exceeded 1.0 kg/m^2/h.Table III presents the recording rate of evaporation in this investigation.

TABLE III: RECORDS FOR THE RATE OF EVAPORATION

Time	Weight of water (kg)	Loss water weight (kg)	Rate of Evaporation (kg/m^2/h)
12:25	2.880	----	----
1:25	2.835	0.045	0.68
2:25	2.750	0.085	1.28
3:25	2.682	0.068	1.03
4:25	2.622	0.060	0.91
5:25	2.562	0.060	0.91

A. Test on Hardened Mortar

The compressive strength test was carried out on nine cube specimens (100×100×100 mm) for each mixture, and tested at 7, 14 and 28 days in accordance with BS 1881: part 116 procedure [24]. Compressive strength test consisted of applying a continuous compressive axial load at a rate of 0.3 MPa/s until failure occurs.The test setup is shown the figure 4.

After casting, the slabs were consolidated using external vibration., the following day, theplastic shrinkage cracks on the hardened mortar surface were mapped to obtain pattern, length of cracking, crack widths and total area of cracking. For mapping 10 cm grid was drawn on the surface of the slabs and the cracks on the slab were mapped on graph sheet. The width of each crack was measured at regular intervals along its length using a microscope. The length of each crack was determined by placing a string along the crack and then measuring the length of string. The summation of product of average width and length of crack for all the cracks in a slab was calculated to obtain total crack area per square meter.

Fig. 4: Compressive strength testing machine.

III. RESULTS AND DISCUSSIONS

3.1 Compressive Strength

The results for the plain and RP fibers mortar (i.e. average of three cubes) compressive strength test are summarized in Table IV.

TABLE IV: COMPRESSIVE STRENGTH OF PLAIN AND RP FIBERS MORTAR

Specimen	Design Mix.	Fiber Volume Fraction (%)	Compressive strength (MPa)		
			7 – Day Average	14 – Day Average	28 – Day Average
Plain	N.F.M.1	0.00	9.70	12.44	13.29
	N.F.M.2	0.00			
Specimen with 20 mm length RPF	R.F.M.3	0.50	9.56	11.12	13.46
	R.F.M.4	0.50			
	R.F.M.5	1.00	10.71	13.25	17.29
	R.F.M.6	1.00			
	R.F.M.7	1.50	11.35	14.60	17.60

	R.F.M.8	1.50			
Specimen with 50 mm length RPF	R.F.M.9	0.50	10.01	12.46	14.35
	R.F.M.10	0.50			
	R.F.M.11	1.00	10.96	14.43	16.63
	R.F.M.12	1.00			
	R.F.M.13	1.50	12.22	16.10	17.73
	R.F.M.14	1.50			

Figures 5a and 5b present the comparison of compressive strength at 7, 14 and 28 days for control and RP fiber contents of length 20 mm and 50 mm respectively. The results indicate an increase in compressive strength of RP fiber mortar compared to plain mortar. At both 7, 14 and 28 days, the increase in compressive strength of RP fiber with volume fractions of 1.0% and 1.5% and length 20 mm were 10.41, 17.00%, 6.51, 17.36% and 30.17, 32.43%, respectively compared to control. The increase in compressive strength with RP fiber with volume fractions were 1.0% and 1.50% in length 50 mm were 12.99, 25.98%, 16.00, 29.42% and 25.13, 33.41%, respectively compare to control. The plain mortar specimens failed in a brittle manner and shattered into pieces. In contrast, all the RP fiber samples after reaching the peak load could remain as integral piece, with fibers holding the mortar matrices tightly together.

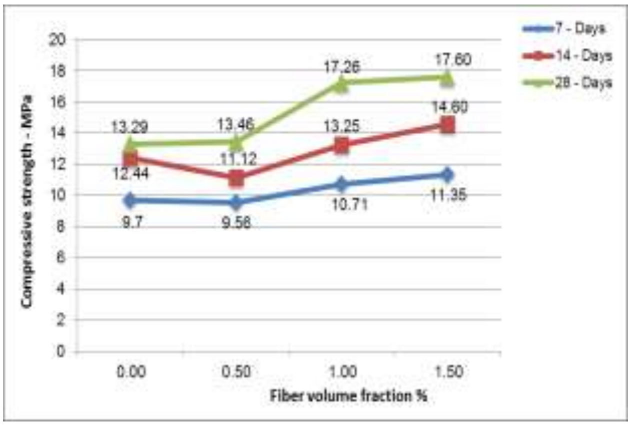


Fig.5a: Compressive strength RP fibers of 20 mm

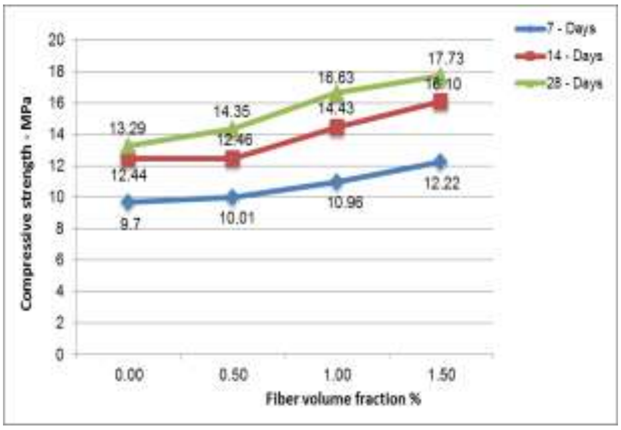
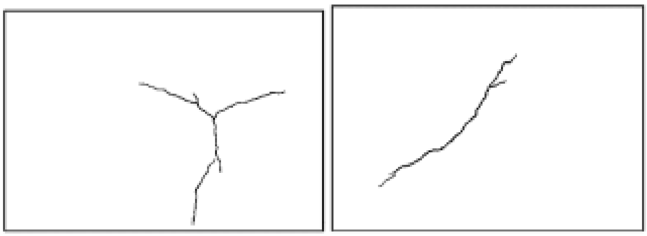


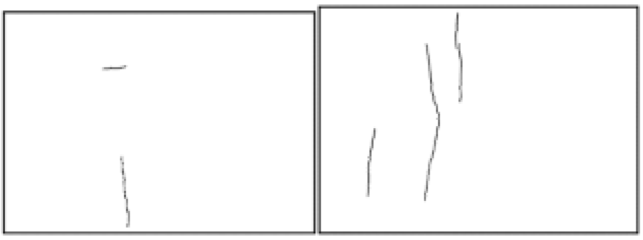
Fig.5b: Compressive strength RP fibers of 50 mm

3.2 Plastic Shrinkage Cracking

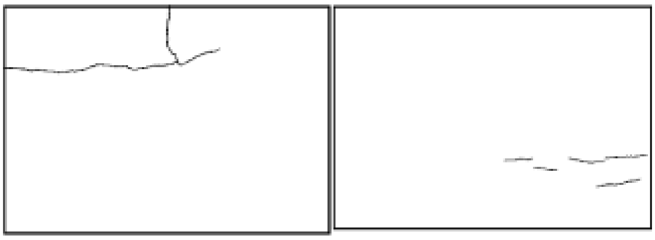
All the plastic shrinkage slabs were placed indoor of laboratory. The average wind speed, ambient temperature and humidity were in the range of 4.0 m/s to 6.5 m/s, 22^0C to 25^0C and 40% to 45% respectively. Plastic shrinkage cracks were mapped for all the slabs. These mapping patterns are presented in (Sketch 5a thru 5g). From these mappings, it is clearly seen that RP fiber mortar with 1.50 % fiber content for50 mm length exhibited less cracking.



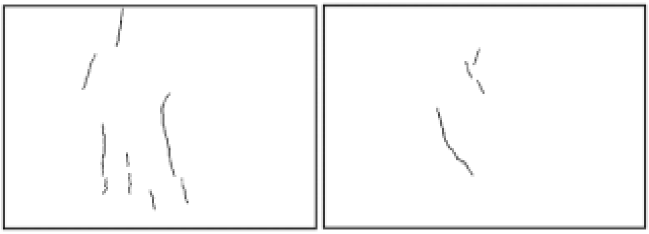
Sketch 5a: Plastic shrinkage cracking at 0% RP fiber



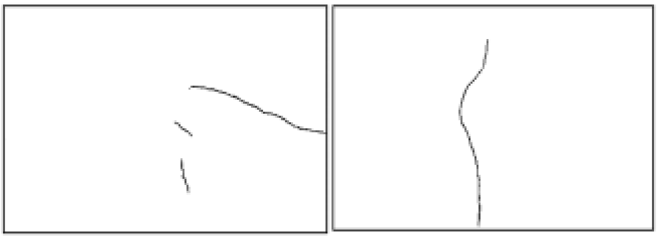
Sketch 5b: Plastic shrinkage cracking 0.50% RP fiber, length20 mm.



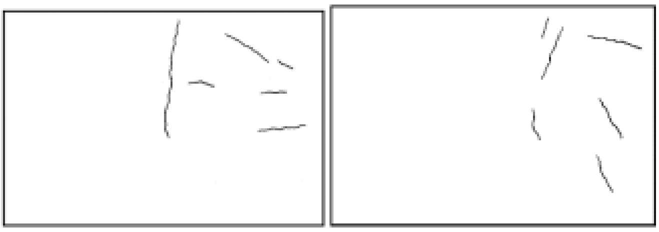
Sketch 5c: Plastic shrinkage cracking 1.0% RP fiber, length 20 mm.



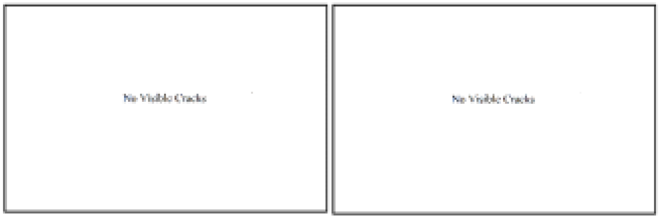
Sketch 5d: Plastic shrinkage cracking 1.50% RP fiber, length 20 mm.



Sketch 5e: Plastic shrinkage cracking 0.50% RP fiber, length 50 mm.



Sketch 5f: Plastic shrinkage cracking 1.0% RP fiber, length 50 mm.



Sketch 5g: Plastic shrinkage cracking 1.50% RP fiber, length 50 mm.

The surfaces of typical plastic shrinkage cracking specimens with the different fiber lengths and volume fractions are shown in (Sketch 5a thru 5g). It can be observed that the plastic shrinkage cracks formed generally parallel to the width of the specimen. For the plain specimens and the specimens with low fiber content 0.50%, one or two straight cracks extended continuously across the entire width of the specimen and grew to a relatively wide size. These few dominant cracks accounted for the majority of the total crack area. For the specimens with high fiber volume fractions, especially those with 1.50% fibers, multiple, relatively fine, indirect and disconnected cracks were observed.

The influence of adding fibers of all lengths and volume fractions on Crack measurements of plastic shrinkage in terms of the average crack width, maximum crack width, average crack length, total crack area and crack numbers is illustrated in Table V. Average crack width was in range 0.14 to 0.79 mm/m, the maximum crack width was in 2.00 mm for plain control specimens, was in ranged from 0.20 to 0.35 mm/m when RP fibers are added for all the slabs. Average crack length was in ranged from511 to 694 mm/m, total crack area was in ranged from 0 to 454 mm^2/m and crack numbers ranged from 1 to 6 cracks for all slabs.

A comparison of crack areas, crack widths, length crack and number of cracks obtained for plain and RP fiber mortar with 20 mm and 50 mm is shown in (Fig 5c thru 5e). The effect of RP fibers on plastic shrinkage is clearly seen in these figures 5c thru 5e. The total crack area, decreased for both lengths of RP fiber of 20 mm and 50 mm with the increasein fibers volume fraction. For the visible cracks, lowest crack width and the lowest crack area was 0.14 mm and 87 mm^2/m for 20 mm and 50 mm length, respectively. This was recorded for 1.50 % RP fiber with 20 mm length.

TABLE V: PLASTIC SHRINKAGE OF PLAIN AND RP FIBERS MORTAR SLABS

Design Mix.	Crack Measurement	Slab 1	Slab 2	Average
	Avg. Crack Width (mm)	0.80	0.79	0.79
N.F.1&2	Max. Crack Width (mm)	1.50	2.5	2.00
	Crack Length (mm)	348	801	574
V_F = 0%	Crack Area (mm^2/m^2)	278	629	454
	Crack Numbers	2	1	1
	Avg. Crack Width (mm)	0.17	0.28	0.22
20L.F.3&4	Max. Crack Width (mm)	0.25	0.35	0.30
	Crack Length (mm)	256	844	550
V_F =0.50%	Crack Area (mm^2/m^2)	43	232	137
	Crack Numbers	2	3	2
	Avg. Crack Width (mm)	0.20	0.17	0.18
20L.F.5&6	Max. Crack Width (mm)	0.25	0.25	0.25
	Crack Length (mm)	751	494	622
V_F = 1.00%	Crack Area (mm^2/m^2)	147	82	115
	Crack Numbers	3	5	4
	Avg. Crack Width (mm)	0.16	0.12	0.14
20L.F.7&8	Max. Crack Width (mm)	0.25	0.2	0.22
	Crack Length (mm)	850	349	599
V_F = 1.50%	Crack Area (mm^2/m^2)	132	42	87
	Crack Numbers	9	4	6
	Avg. Crack Width (mm)	0.20	0.18	0.19
50L.F.9&10	Max. Crack Width (mm)	0.35	0.35	0.35
	Crack Length (mm)	717	672	694
V_F = 0.50%	Crack Area (mm^2/m^2)	143	123	133
	Crack Numbers	3	1	2
	Avg. Crack Width (mm)	0.18	0.25	0.22
50L.F.11&12	Max. Crack Width (mm)	0.3	0.35	0.32
	Crack Length (mm)	530	493	511
V_F = 1.00%	Crack Area (mm^2/m^2)	97	121	109
	Crack Numbers	6	6	6
	Avg. Crack Width (mm)			0
50L.F.13&14	Max. Crack Width (mm)			0
	Crack Length (mm)	No Cracks	No Cracks	0
V_F = 1.50%	Crack Area (mm^2/m^2)			0
	Crack Numbers			0

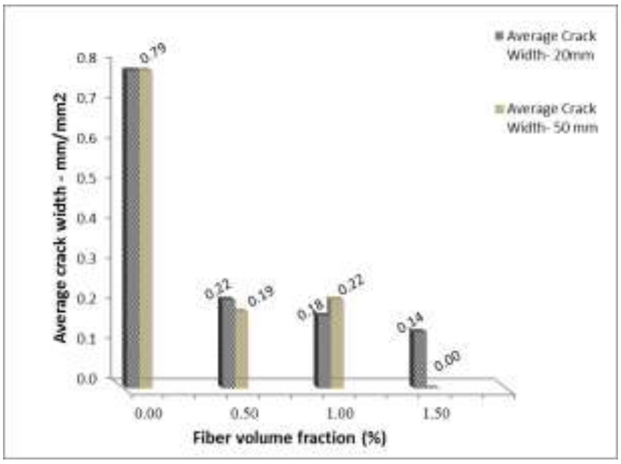


Fig. 5c : Crack width of RP fibers for both lengths

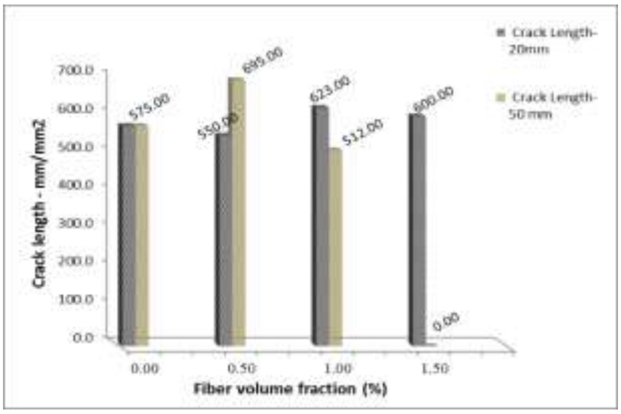


Fig. 5d : Crack length of RP fibers for both lengths

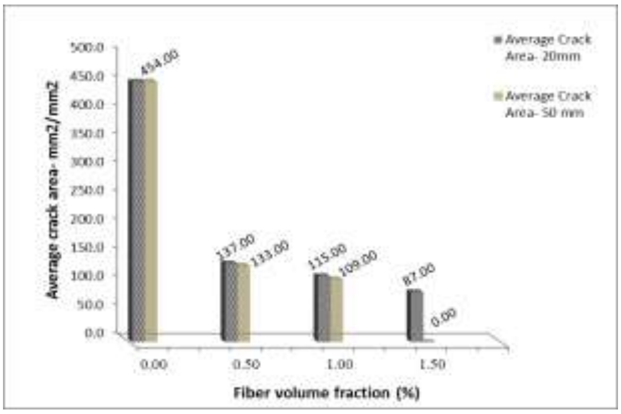


Fig. 5e : Crack area of RP fibers for both lengths

As a first observation, it is clear that the RP fiber was more effective in controlling plastic shrinkage cracking compared with 50 mmlong fibers. Both total crack areas and average crack widths were significantly reduced by the addition of RP fibers at all three volume fractions. Considered compared with plain specimens, the total crack area was reduced by 69.82%, 74.67% and 80.83%when0.50%, 1.00% and 1.50% volume fraction of 20 mm RP fibers, respectively were added,the average crack widthwas reduced by72.15%, 77.21% and 82.28% when 0.50%, 1.00% and 1.50% volume fraction of 20 mm RP fibers, respectively were added. At 0.5% and 1.0% volume fraction of 50 mm RP fibers, the total crack area was reduced by 70.71% and 76.00% respectively,the average crack width was reduced by 75.95% and 72.15% respectively, the total crack area and average crack widths were compared with plain specimen while at a volume fraction of 1.5 % no plastic shrinkage cracks were observed.

At the 1.50% volume fraction, for both fibers lengths caused multiple small cracks; and therefore, the crack numbers increased significantly. The reason for the occurrence of multiple small cracks is thought to be related to the bridging forces provided by the fibers. Since there were more fibers bridging a crack at high volume fractions, they effectively held the faces of the crack together, preventing it from growing.

As a result, the improved performance of certain fiber length can be attributed largely to their increased surface area relative to other fiber length. Higher surface areas permit the fibers to improve the tensile strength of the matrix and bridge the cracks more effectively.

IV. CONCLUSION

This study was conducted mainly to investigate the potential of using recycled plastic fibers to reduce plastic shrinkage cracking. Based on the results of this investigation following conclusions are made:

- At volume fraction of 0.50% of RP fibers, plastic shrinkage cracking were almost similar to plain mortar without RP fibers (i.e., 0.0%). However, at a volume fraction of 1.00 to 1.50%, no plastic shrinkage cracks were observed. A significant improvement in controlling the plastic shrinkage cracking was found by increasing the fiber volume fraction over a range from 0.50% to 1.50%.
- Both total crack areas and average crack widths were significantly reduced by the addition of RP fibers at all three volume fractions. The total crack areas and average crack widths were decreasing of length 50 mm than the total crack area and average crack widths of 20 mm for RP fibers, while at a volume fraction of 1.5% for length 50 mm no plastic shrinkage cracks were observed.
- As a result, the RP fibers of 50 mm had more surface area than the RP fibers of 20 mm at a given volume fraction. They were therefore able to improve the tensile strength of matrix and bridge the cracks more effectively.
- The number of cracks generally increased with increasing fiber volume fraction, When 1.00% and 1.50% volume fractions were added, the increase in crack numbers were relatively small.
- RP fibers have significant effect on the compressive strengths of plain mortar at volume fractions used in this study. However, the RP fibers increased compressive strengths up to 33.41%. By increasing the volume fraction for both lengths of RP fibers the compressive strength increased especially for length of 50 mm.

ACKNOWLEDGMENT

The authors acknowledge the support provided by the Department of Civil Engineering and the General Directorate for Research Grants, King Abdul-Aziz city for Science and Technology.

REFERENCES

[1]. Balaguru PN, Shah SP. Fiber reinforced cement composites. McGraw-Hill International Editions; 1992.
[2]. Bentur A, Mindess S. Fiber reinforced cementitious composites. London: Elsevier Applied Science; 1990 , 1–11.
[3]. Won JP, Park CG. Shrinkage cracking and durability characteristics of polypropylene fiber reinforced concrete. J KSCE 1999 ;15(5): 783–90.
[4]. Wang K, Shah SP, Pariya P. Plastic shrinkage cracking in concrete materials influence of fly ash and fibers. ACI Mater J 2001 ;96(6): 458–64.
[5]. Naaman AE, Xia Z, Hikasa JI, Saito T. Control of plastic shrinkage cracking of concrete with PVA fibers. In: Proceedings of international symposium on infrastructure regeneration and rehabilitation. UK: University of Sheffield; 1999, p. 371–85, June 28–July 2.
[6]. Kraai PP. A proposed test to determine the cracking potential due to drying shrinkage of cracking. Concrete Construct 1985 ; 30(9):775–8.
[7]. Grzybowshi M, Shah SP. Shrinkage cracking of fiber reinforced concrete. ACI Mater J, 1991 ;87(2):138–48.
[8]. Toledo Filho, R.D. and Sanjuán, M.A. Effect of low modulus sisal and polypropylene fiber on the free and restrained shrinkage of mortars at early age. Cement and Concrete Research, 1999 ; 29(10): 1597-1604.
[9]. Bayasi, Z. and Mclntyre, M. Application of fibrillated polypropylene fibers for restraint of plastic shrinkage cracking in silica fume concrete. ACI Materials Journal, 2002 ; 99(4): 337-344.
[10]. Qi, C. Quantitative assessment of plastic shrinkage cracking and its impact on the corrosion of steel reinforcement. Ph.D. Thesis, Department of Civil Engineering, Purdue University, West Lafayette, Indiana, USA. 2003.
[11]. Sung Bae Kim, Na Hyun Yi, Hyun Young Kim, Jang-Ho Jay Kim, Young-Chul Song. Material and structural performance evaluation of recycled PET fiber reinforced concrete, Cement & Concrete Composites 32, 2010 , pp. 232-240.
[12]. The Korean Institute of Resources Recycling, Recycling handbook, Korea: The Korea Institute of Resources Recycling; 1999 . pp. 195-206.
[13]. Wang Y., Wu H. C. and Li V. C. Concrete reinforcement with recycled fibers. Journal of Materials in Civil Engineering. 2000 , 12, No.4, pp. 314-319.
[14]. Auchey F. L. The use of recycled polymer fibers as secondary reinforcement in concrete structures. Journal of Construction Education. 1998, 3, No.2, pp. 131-140.
[15]. Sehaj S, Arun S, Richard B. Pullout behavior of polypropylene fibers from cementitious matrix. Cement Concrete Research, 2004 , 34(10), pp. 1919–1925.
[16]. Zollo RF. Fiber-reinforced concrete: an overview after 30 years of development. Cement Concrete Comp 1997 , 19(2), pp. 107–22.
[17]. Mwangi JPM. Flexural behavior of sisal fiber reinforced concrete beams. PhD thesis. University of California Davis; 2001.
[18]. Aulia TB. Effects of polypropylene fibers on the properties of high-strength concrete. Leipzig Annual Civil Engineering Rep 2002 , 5. pp. 43–59
[19]. Alhozaimy A. M. and Alshannag M. J. Performance of concrete reinforced with recycled plastic fibers. Magazine of Concrete Research. 2009 , 61, No. 4, May, pp. 293-298.

[20]. Alshannag MJ, Brinker R, Hansen W. Pullout behavior of steel fibers from cement-based composites. Cement Concrete Res 1997 ;27(6):925–36.
[21]. Li VC, Chan YW, Wu HC. Interface strengthening mechanisms in polymeric fiber reinforced cementitious composites. In: Proceeding of International Symposium of Brittle Matrix Composites, Warsaw, September 13–15,1994 . Warsaw: IKE and Woodhead Publish.; 1994 . p.7–16.
[22]. Wong tanakitcharoen T. Effect of randomly distributed fibers on plastic shrinkage cracking of cement composites, PhD Thesis, Ann Arbor, USA: University of Michigan; 2005. p. 149.
[23]. Mobasher B, Li CY. Effect of interfacial properties on the crack propagation in cement based composites. Adv. Cement Based Mater 1996 ;4(3–4):93–105.
[24]. British Standards Institution, BS 1881-116, "Method for determination of compressive strength of concrete cubes", London, 1983.