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Maximum crack spacing model for Irregular-shaped Polyethylene Terephthalate fibre reinforced concrete beam

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Abstract—**This paper reports the results of an experimental study of reinforced concrete (RC) beam conducted using irregular-shaped Polyethylene Terephthalate (IPET) as fibre. Three volume fraction of IPET fibre are used namely, 0.5%, 1% and 1.5%. All RC beam specimens are tested under four point loading under flexural capacity behaviour. The results for maximum crack spacing under cracking behaviour are reported. The results than are compared with three models namely, Gilbert model, EC2 1997 and CEB-FIP 1990 to determine the most reliable approach than match with the experimental results. It is found that the addition of IPET fibre improves the crack spacing of RC beams proportional to the increment of volume fraction of IPET fibre. None of the models mentioned above considered the fibre factor. Therefore, a modification of the most reliable model are carried out and proved with the statistical analysis tool to consider IPET fibre factor. At the end of this paper, a modified model is carried out for future research that has same parameters with this research.**

Keywords—**Irregular-shaped Polyethylene Terephthalate (IPET) fibre, mechanical properties, deflection behaviour, maximum crack spacing, maximum crack spacing model, and reinforced concrete (RC) beam.**

I. Introduction

Theoretically, concrete is reinforced with steel bar with its characteristic weakness in tension, where steel reinforcement is used to carry the tensile forces across the cracks [1]. Once the concrete itself has exceeded its tension capacity, the first crack started to occur at the weak section along the structure [2]. At the crack section, the compatibility of strain between concrete and reinforcement is no longer maintained due to the concrete stress drops to zero and the steel reinforcement carry the overall stresses of the RC beam. The role of steel reinforcement prevents the crack from widening and avoids brittle failure in RC beam structure [1] [2].

The role of fibre inside concretes it to bridge across the cracks when the strain of the composite has exceeded the ultimate strain capacity of the brittle [3]. Previous researches [4] [5] [6] [7] as stated in Table I indicate the shape of PET fibre used in their research. As the irregular type of Polyethylene Terephthalate (PET) from recycled bottle wastes are yet to be studied and one of the potential means to the problem is to recycle the wastes in construction industry [8], therefore, in this research, the irregular-shaped Polyethylene Terephthalate (IPET) is appointed to be the fibre in concrete to test its performance.

TABLE I. SUMMARY OF PREVIOUS RESEARCH

Research	Year	Volume fraction of PET fibre [%]	Shape of PET fibre	Water-cement ratio
Kim	2010	0.50, 0.75, 1.00	Strip	0.41
Fraternalli	2011	1.00		0.53
Foti	2011	0.26	Strip & circular	0.70
Ochi	2007	0.50, 1.00, 1.50	Monofilament	0.55, 0.60, 0.65

II. Experimental tests

Mix proportions for the concrete and beam designation is as indicated in Table II and III. In this research, self compacting concrete (SCC) is used in concrete casting with Ordinary Portland cement complied with EN 197 - 1 [9]. Sand with maximum size of 4.75 mm and crushed gravel (12-20 mm) with a density of 980 and 805 kg/m^3 is used as fine and coarse aggregates. Fly ash (FA) Class F is used as binder agent. Superplasticizer (SP) used was Mighty 21 VS from Kao Malaysia [10] and is conformed to EN 934 - 2 [11]. The water cement (W/C) ratio is fixed at 0.58. This mix proportion is based on the trial mix done in Irwan [8] to achieve a concrete

TABLE II. MIX PROPORTION OF CONCRETE

Mix proportion	
	Unit weight (kg/m^3)
Cement (C)	300
Fly Ash (FA)	90
Sand (S)	980
Gravel (G)	805
Water (W)	175
W/C Ratio	0.58
	Volume (ml)
Superplasticizer	4680

TABLE III. RC BEAM DESIGNATION AND IPET VOLUME FRACTION

Batch	PET (%)	Beam designation
1	-	B-0-1A & B-0-2B
2	0.5	B-0.5-1A & B-0.5-2B
3	1.0	B-1-1A & B-1-2B
4	1.5	B-1.5-1A & B-1.5-2B

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strength of 30 MPa and the mix is complied with European Guideline on SCC [12]. For the recycled IPET fibre, the fibre used in this research is obtained from the recycled bottle wastes from recycle collector. The bottle wastes than are grinded using granulator machine and sieved as in Fig. 1 and 2. The grinded IPET bottles in irregular shape retained at five to ten mm are used as IPET fibre in this research. Table IV summarizes the properties of PET fibre used in this research. The concrete material properties tests namely, compressive strength (f_{cu}), tensile strength (f_{ct}) and modulus of elasticity (E_c) are followed by EN 12390 - 3:2000 [13], EN 12390 - 6:2000 [14] and BS 1881 - 121:1983 [15].

Figure 1. IPET fibre used in this research

Figure 2. Granulator machine used to grind recycled bottle wastes to produce IPET fibre

TABLE IV. PROPERTIES OF IPET USED IN THIS RESEARCH

PET (%)	Dimension (mm)	Density (kg/m^3)	Tensile strength (MPa)	Ultimate elongation (%)
-		-	-	-
0.5		0.9		
1.0	5-10	1.8	180	10-20
1.5		2.7		

A total of eight RC beams (2300x300x100 mm) specimens are tested under flexural capacity test setup after 28 days from casting. All specimens are reinforced with four T12 reinforcement bars; with two at the bottom (tensile reinforcement) and two on top (compressive reinforcement), R6 shear stirrups with 100 mm spacing. The testing instrumentation setup is shown in Fig. 3 and 4. RC beams specimens with pinned and roller supports are tested using Universal Test Frame (UTF) with maximum load capacity of 3000 kN. The load is applied using manually controlled hydraulic jack with the loading rate of 1 kN/min.. In order to obtain an accurate deflection measurement, a Linear Variable Differential Transducer (LVDT) is placed at three positions; mid span, and both sides under point loadings. Crack spacing is measured by the average distance from one crack to another crack as in Fig. 5 and maximum crack spacing indicates as S_{max} [2].

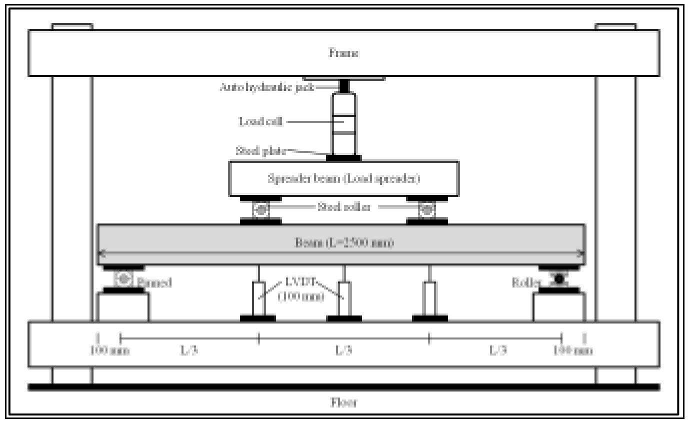

Figure 3. Flexural capacity test setup

Figure 4. Flexural capacity test setup

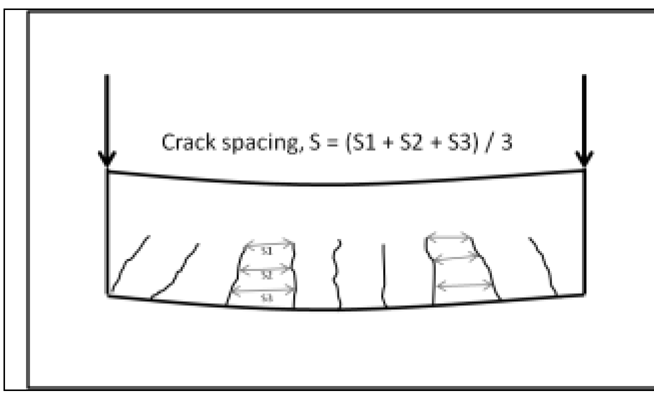

Figure 5. Crack spacing measurement in concrete surface

III. Results and analysis

The results and analysis are categorized in three section namely, mechanical properties, and maximum crack spacing.

A. Mechanical Properties

The results for compressive strength (f_{cu}), splitting tensile strength (f_{ct}) and elastic modulus (E_c) are shown in Table V. The f_{cu} for all batches of concrete in this research is passed the concrete Grade 30. The f_{cu} for normal concrete is 36.03 MPa. The addition of PET fibre at 1% and 1.5% of volume fraction decrease the f_{cu} at about 5 to 6.4% whereas 0.5% volume fraction PET fibre exhibits increasing in concrete strength at 0.5%. The f_{ct} for normal concrete is 3.4 MPa. Increments of 8.8 to 17.6% in f_{ct} are observed with the addition of PET fibre in concrete. The same trend for E_c is observed where the increment of 1.2 to 3.9% is figured out. The mechanical properties observed in this research are slightly improved compare to research done by Kim [4]. In that research, the f_{cu} and E_c exhibited decreased by 1 to 9% and 1 to 10% compared to normal concrete specimens. The increments in f_{ct} proportional to the PET fibre volume fraction are expected to improve structural performance in further discussion.

TABLE V. RESULTS OF MECHANICAL PROPERTIES OF CONCRETE

Batch	PET (%)	Ave. f_{cu} (MPa)	Ave. f_{ct} (MPa)	Ave. E_c (MPa)
1	-	36.03 ± 0.208	3.41 ± 0.010	25510 ± 177.553
2	0.5	36.23 ± 0.306	3.72 ± 0.015	25806 ± 165.973
3	1.0	34.23 ± 0.451	3.91 ± 0.208	26076 ± 51.215
4	1.5	33.73 ± 0.777	4.02 ± 0.067	26502 ± 185.914

B. Maximum crack spacing

Results for maximum crack spacing are shown in Table VI. From the results, it shows that the maximum crack spacing for control RC beams specimens; B-0-1A and B-0-2B is 152.50 ± 3.535 mm. When the RC beams specimens introduce with IPET fibres at vary volume fraction, different results are observed. RC beams specimens namely; B-0.5-1A, B-0.5-2B, B-1-1A, B-1-2B, B-1.5-1A and B-1.5-2B have indicated the maximum crack spacing 151.50 ± 0.707 mm, 167.50 ± 7.778 mm and 187.50 ± 17.678 mm respectively. Therefore, it can be concluded that the addition of IPET fibres in RC beams have increased the maximum crack spacing length by 9.8% to 23% respectively.

TABLE VI. RESULT OF MAXIMUM CRACK SPACING

No of batch	Beam designation	$P_{ultimate}$ (kN)	$S_{,max}$ (mm)	
1	B-0-1A	120	150	152.50 ± 3.535
	B-0-2B	119	155	
2	B-0.5-1A	122	151	151.50 ± 0.707
	B-0.5-2B	123	152	
3	B-1-1A	125	162	167.50 ± 7.778
	B-1-2B	125	173	
4	B-1.5-1A	128	200	187.50 ± 17.678
	B-1.5-2B	127	175	

IV. Modification of Crack Spacing Model

Three crack spacing model namely; Gilbert model [16], EC 2 1997 approach [17] and CEB-FIP 1990 approach [18] are compared based on the experimental work performed. Based on these three models, the maximum crack spacing (S_{max}) is carried out to get the best model for this research.

A. Gilbert Model

The crack spacing model from Gilbert model [16] is shown in following in (1). In this model, the maximum crack spacing model was proposed. Table VII shows the crack spacing values analysed using Gilbert model [16]. ϕ defines as reinforcement, τ_b defines as bond stress concrete and ρ_{te} defines as effective reinforcement ratio.

$$S_{max} = (f_{ct} .\phi) / (2\tau_b .\rho_{te}) \quad (1)$$

TABLE VII. MAXIMUM CRACK SPACING VALUES ANALYSED USING GILBERT MODEL [16]

Beam designation	$S_{,max}$ (mm) Experimental work		Gilbert model	Ave. Gilbert model	Ratio of experimental results over Gilbert model
B-0-1A	150	152.50 ± 3.535	191.997	192.279 ± 0.399	0.793
B-0-2B	155		192.561		
B-0.5-1A	151	151.50 ± 0.707	210.067	210.349 ± 0.399	0.720
B-0.5-2B	152		210.631		
B-1-1A	162	167.50 ± 7.778	219.667	219.949 ± 0.399	0.762
B-1-2B	173		220.231		
B-1.5-1A	200	187.50 ± 17.678	223.055	224.184 ± 1.597	0.836
B-1.5-2B	175		225.313		

B. EC 2 1997 and CEB-FIP 1990

For EC 2 1997 [17] and CEB-FIP 1990 [18] approaches, (2) and (3) shown the theoretical equation. Table VIII and IX show the maximum crack spacing results calculated using both approaches. In (2), k_1 and k_2 define as 0.8 (deformed reinforcement bars) and 0.5 (bending) while $\rho_{s,eff}$ defines as effective reinforcement ratio. In (3), $l_{s,max}$ is the stabilized crack approximately the maximum crack spacing [18].

$$S_{rm} = 50 + (0.25k_1k_2\phi) / \rho_{s,eff} \quad (2)$$

$$l_{s,max} = (\phi) / 3.6\rho_{s,eff} \quad (3)$$

TABLE VIII. MAXIMUM CRACK SPACING VALUES ANALYSED USING EC 2 1997 [17]

Beam designation	Stabilized (maximum) crack spacing (mm)			Ratio of experimental results over EC 2 1997 approach
	Experimental work		EC 2 1997 approach	
B-0-1A	150	152.50 ± 3.535	168.812	0.904
B-0-2B	155			
B-0.5-1A	151	151.50 ± 0.707		0.897
B-0.5-2B	152			
B-1-1A	162	167.50 ± 7.778		0.992
B-1-2B	173			
B-1.5-1A	200	187.50 ± 17.678		1.111
B-1.5-2B	175			

TABLE IX. MAXIMUM CRACK SPACING VALUES ANALYSED USING CEB-FIP 1990 [18]

Beam designation	Stabilized (maximum) crack spacing (mm)			Ratio experimental results over CEB-FIP 1990 approach
	Experimental work		CEB-FIP 1990 approach	
B-0-1A	150	152.50 ± 3.535	330.033	0.462
B-0-2B	155			
B-0.5-1A	151	151.50 ± 0.707		0.459
B-0.5-2B	152			
B-1-1A	162	167.50 ± 7.778		0.508
B-1-2B	173			
B-1.5-1A	200	187.50 ± 17.678		0.568
B-1.5-2B	175			

Table X summarizes all models and the parameters considered in each model. Approach by CEB-FIP 1990 [18] is considered to be ignored because the ratio shows the lowest (0.459 to 0.568) compared to Gilbert [16] and EC 2 1997 [17]. Approach by EC 2 1997 [17] shows the close ratio (0.897 to 1.111) but the parameter considered in (2) is insufficient where only $\rho_{s,eff}$ and ϕ are stressed. In this research, the addition of IPET fibre has influenced the f_{ct} and the increment in S_{max} analysed is influenced due to this factor. Therefore, a modification of model is carried out that considered f_{ct}. Throughout all models considered above, none of them are considered PET fibre factor in their model. As consequent, Gilbert model [16] is chosen to be modified as this model is the most significant where f_{ct} in which influence by IPET fibre included in this model.

TABLE X. COMPARISON OF FACTOR CONSIDERED OF EACH MODEL

Parameter consider	Model		
	Gilbert	EC 2 1997	CEB-FIP 1990
Concrete tensile, (f_{ct})	√	-	-
Concrete bond stress, (τ_b)	√	-	-
Effective reinforcement ratio, (ρ_{te})	√	√	√
Reinforcement bar diameter, (ϕ)	√	√	√
Fibre factor, F	-	-	-
Model + IPET (Modification)	Significant	-	-

C. *Modification of Gilbert Model*

Gilbert model in (1) [16] is appointed to be modified because it is the most significant model to this research. Table XI shows the data on IPET fibre aspect ratio. IPET fibre factor, F is calculated using (4) according to Minelli [19] and stated in Table 11. V_f is defined as IPET fibre volume fraction. The propose model from Gilbert model [16] that consider F in the equation shown in (5). α, β and κ are considered as the factor for each variable in (5). Then, (5) is examined with statistical tool to for validation

TABLE XI. IPET FIBRE ASPECT RATIO

Batch	PET length, L_f (mm)	PET thickness, D_f (mm)	PET fibre aspect ratio, (L_f/D_f)	Ave. PET fibre aspect ratio, (L_f/D_f)
1	7.10 ± 1.077	0.214 ± 0.008	33.178	32.025 ± 1.513
2	6.94 ± 0.916	0.218 ± 0.010	31.835	
3	7.09 ± 0.836	0.214 ± 0.008	33.131	
4	6.83 ± 0.578	0.228 ± 0.010	29.956	

$$\text{IPET fibre factor, } F = V_f\,(L_f/D_f) \quad (4)$$

$$S_{max,IPET} = \alpha\,(S_{max}) + \beta\,(F) + \kappa \quad (5)$$

The results on statistical analysis are shown in Table XII. From the results, it shows that the coefficient of determinant (R^2), T-test and t-statistic for (5) are significant. Therefore, the new modified model in (6) is proposed to be used in this research. Table XIII shows the $S_{max,IPET}$ results calculated using (6). From the results, it shows that the ratio of experimental results over theoretically calculation using (6) is 0.995 to 1.012 and this pattern indicate using (6) to determine maximum crack spacing in this research is significant as in Table XIV. The results answered the theory of fibre in concrete where the fibre has bridged along concrete surface [3] and therefore, the maximum crack spacing increase by 0.7 to 23% correspondent to the volume fraction of IPET fibre added respectively.

TABLE XII. COEFFICIENT OF DETERMINANT (R^2), CRITICAL T AND T-STATISTIC VALUE

<table>
<tr><th>Modified Equation Model</th><th>R</th><th>R^2</th><th>Result</th></tr>
<tr><td rowspan="8">$S_{mat\ IPET}$ (5)</td><td>0.919</td><td>0.845 > 0.5</td><td>Significant</td></tr>
<tr><td>Critical t value</td><td>T > t</td><td>Result</td></tr>
<tr><td>2.015</td><td>2.824 > 2.015</td><td>Significant</td></tr>
<tr><td>t-statistic</td><td>|t statistic| ">" or "<" Critical t-value</td><td>Result</td></tr>
<tr><td>Constant</td><td>3.075 > 2.015</td><td>Significant</td></tr>
<tr><td>IPET fibre factor</td><td>3.423 > 2.015</td><td>Significant</td></tr>
<tr><td>S_{max} (Gilbert Model)</td><td>2.149 > 2.015</td><td>Significant</td></tr>
</table>

$$S_{max,IPET} = 486.014 - 1.733(S_{max}) + 1.895(F) \quad (6)$$

TABLE XIII. S_{MAX} RESULTS CALCULATED USING (6)

Beam designation	$S_{,max}$ (mm)			Modification of Gilbert model, $S_{max,IPET}$ (mm)	Ave. modification of Gilbert model, $S_{max,IPET}$ (mm)
	Exp. work		Gilbert model		
B-0-1A	150	152.50 ± 3.535	191.997	152.306	152.795± 0.691
B-0-2B	155		192.561	153.283	
B-0.5-1A	151	151.50 ± 0.707	210.067	152.313	151.824 ± 0.692
B-0.5-2B	152		210.631	151.335	
B-1-1A	162	167.50 ± 7.778	219.667	166.018	165.530 ± 0.691
B-1-2B	173		220.231	165.041	
B-1.5-1A	200	187.50 ± 17.678	223.055	190.492	188.536 ± 2.767
B-1.5-2B	175		225.313	186.579	

TABLE XIV. RATIO OF EXPERIMENTAL RESULTS OVER $S_{MAX,IPET}$ (6)

Beam designation	Average maximum crack spacing (mm)		Ratio of experimental result over max. crack spacing of modify Gilbert model
	Experimental result	Modification of Gilbert model, $S_{max,IPET}$	
B-0-1A B-0-2B	152.50 ± 3.535	152.795 ± 0.691	0.998
B-0.5-1A B-0.5-2B	151.50 ± 0.707	151.824 ± 0.692	0.998
B-1-1A B-1-2B	167.50 ± 7.778	165.530 ± 0.691	1.012
B-1.5-1A B-1.5-2B	187.50 ± 17.678	188.536 ± 2.767	0.995

V. Conclusion

In this research work, IPET fibre from recycled bottle wastes has been identified improve structural performance of concrete. The environmental and ecological benefit of effectively utilizing this waste material is another prime contribution to this research. The summarize of material and structural performance of concrete in this research are as follows;

- For mechanical properties of concrete, the addition of IPET fibre at 1% and 1.5% of volume fraction decrease the f_{cu} at about 5 to 6.4% whereas 0.5% volume fraction IPET fibre exhibits increasing in concrete strength at 0.5%. The f_{ct} and E_c of concrete added with PET fibres increase at 9.1 to 17.9% (f_{ct}) and 1.2 to 3.9% (E_c)
- The new modified equation (6) to predict the maximum crack spacing (S_{max}) with IPET fibre for future research that has the same parameters with this study.

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